# EFFECTS OF PETROLEUM HYDROCARBON CONCENTRATION AND BULK DENSITY ON THE HYDRAULIC PROPERTIES OF LEAN OIL SAND OVERBURDEN AND WATER STORAGE IN OVERLYING SOILS

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# ABSTRACT

Coarse textured soils with low water and nutrient retention are commonly the only available materials for reclamation of the projected 480,000 hectares of disturbed land in the Alberta oil sands. It is important to understand the processes in the soils being used for reclamation to be able to re-create conditions that occurred prior to disturbance. Extensive research has been conducted to understand the hydraulic processes in mineral soils, however much of the soils that are used for reclamation in the Alberta oil sands are impregnated with petroleum hydrocarbons (PHCs). Little is known of the effects of PHCs on soil hydraulic properties. Lean oil sand (LOS) is an overburden material that contains PHCs, and is considered mine waste. LOS must be reclaimed, and is currently being tested as the base soil layer for some of the reclamation being conducted in the Alberta oil sands. It is important to understand how the hydraulic properties in the LOS as well as in the overlying reclamation soils will be affected by PHCs. The main objective of this thesis is to determine the efficacy of using LOS as a base soil layer on the successful reclamation of disturbed land in the Alberta oil sands. This was done by: 1) Evaluating how PHCs and bulk density influence the hydraulic properties of LOS and 2) Determining how the soil hydraulic properties in the layers overlying the LOS are affected by the heterogeneity of PHC concentration and bulk density of the LOS.

Soil cores were packed with LOS with varying PHC concentrations and bulk densities to test water retention curves and saturated hydraulic conductivity of the LOS. Soil columns were packed with a base LOS layer and reclamation cover soils that are used in the Alberta oil sands. The soil columns were used to test water and nutrient dynamics in the reclamation soil profile. It was found that both bulk density and PHC concentration had an effect on the hydraulic properties in LOS as well as in the overlying reclamation profile. The porosity of soil is largely

affected by bulk density, so as bulk density of the LOS increased, it lead to lower water retention at saturation, but higher water retention at soil suctions associated with field capacity and permanent wilting point (PWP). This led to LOS at higher bulk densities having higher available water holding capacity (AWHC) and lower $K_s$, providing the overlying soil profile with more water and nutrients for a longer time for plants to access. Furthermore, PHCs reduced water retention in LOS due to plugging mainly the soil micropores pores and connecting porosity. This lead to lower $K_s$ of the LOS, which resulted in an increased water and nutrient retention in the overlying soil profile. Results show that the use of LOS in the reclamation of coarse textured soils in the Alberta oil sands can aid in creating suitable soil conditions leading to reclamation success.

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# List of Abbreviations

| | |
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| ANOVA: | analysis of variance |
| ASCS: | Aurora Soil Capping Study |
| AWHC: | available water holding capacity |
| BWE: | breakthrough water equivalent |
| CEMA: | Cumulative Effects Monitoring Association |
| EC: | electrical conductivity |
| LOS: | lean oil sand |
| PHC: | petroleum hydrocarbon |
| PSA: | particle size analysis |
| PWP: | permanent wilting point |
| TDR: | time domain reflectometry |
| U of S: | University of Saskatchewan |

# 1.0 INTRODUCTION

## 1.1 Background

The leading method of energy production globally is the burning of non-renewable fossil fuels such as coal and processed crude oil. In 2012, North America alone consumed almost 23,000 thousand barrels per day (Tbbl $d^{-1}$) of oil (U.S. EIA, 2014). Until alternative energy production methods such as renewable resources (solar and wind) and nuclear energy become more efficient and widely used, the burning of fossil fuels will continue to dominate energy production. Within the soil of Northern Alberta, lies one of the largest oil reserves in the world, named the Alberta Oil Sands. This accessible deposit of hydrocarbon rich soil has led to crude petroleum oils becoming Canada's top export (Trade Data Online, 2014). With major projects such as the Northern Gateway Pipeline and the Keystone Pipeline being proposed, the export of Canada's crude petroleum oils will increase, and consequently the mining of oil sand deposits (specifically the Alberta Oil Sands) will intensify.

The Alberta Oil Sands underlie approximately 140,000 $km^2$ of boreal forest in Northern and Eastern Alberta (Johnson and Miyanishi, 2008). Of this 140,000 $km^2$, about 4800 $km^2$ will be affected by open pit mining techniques (GOA, 2009). These mining techniques involve stripping the nutrient rich top-soils, sub-soils and overburden materials, and creating pits up to 100 m deep in order to access the hydrocarbon rich oil sand material (Trites, 2009a). This process is highly destructive to the environment, as it removes entire ecosystems from the landscape. The Environmental Protection and Enhancement Act of Alberta (1993) states that oil sands disturbed land must be restored to an equivalent land capability of what it was prior to disturbance. This requires that large swaths of cleared and excavated land be replaced and re-vegetated in the effort to create a self-sustaining ecosystem. It is in the best interest of the companies holding the lease to the land to successfully restore the disturbed area as they are required by law to reclaim the land, and if unsuccessful, plans to re-visit their attempts at reclamation would come at great financial cost. Thus, there are currently many studies underway determining the most effective methods of oil sands reclamation as well as addressing their associated challenges.

The Northern Alberta boreal forest contains a variety of ecosites, each exhibiting different conditions and characteristics that make each ecosite type unique. In reclamation, it is important to consider these specific characteristics in order to re-create the ecosite that was present in the area prior to disturbance. The moisture regime of the soil is a key factor in dictating which type of ecosite will occur (Zettl er al., 2011). Therefore, it is important to be able to re-create soil conditions that will support specific moisture regimes. One of the main challenges associated with oil sands reclamation in the area where the study site is located, is the poor water holding capacity of the available soil. The soils used in the reclamation of oil sands are the naturally occurring soils that were excavated in the process of reaching the hydrocarbon rich oil sands. Many of these soils, due to their coarse texture, have a low water holding capacity and therefore allow water and nutrients to easily flow through the profile to areas that are out of reach of plant roots. This can be a major issue for the establishment and growth of newly planted trees on a reclaimed site. For this reason, it is important to understand the hydraulic processes of the soil in order to create the necessary conditions that will support the early establishment and growth of newly planted vegetation as well as to ensure the long term growth and sustainability of the reclaimed land.

## 1.2 Study Site Overview

The Aurora Soil Capping Study (ASCS) is a long term instrumented watershed research site located North of Fort McMurray, Alberta at Syncrude Canada Ltd.'s Aurora North Mine. The ASCS is designed to test the efficacy of a variety of soil layer prescriptions in a reclamation setting, using the naturally occurring coarse textured soils that were excavated during the mining of oil sands in that area. The soil capping study at the ASCS is a collaborative effort by multiple oil sands companies and universities who are studying many different aspects of oil sands reclamation. The ASCS contains twelve different soil layer prescriptions; each replicated three times over 36 individual 1 ha plots. A major component of the ASCS is the inclusion of a material called lean oil sand (LOS). LOS makes up the foundation on which all reclamation materials are placed across the entire 36 ha area. LOS is the overburden material that overlies the rich oil sand and has a low petroleum hydrocarbon (PHC) concentration, ranging from less than 1% to 8% PHC by weight. Due to the low PHC concentration, it is uneconomical for the PHCs to be extracted, so the LOS is excavated and placed in stockpiles. At the ASCS, the LOS is being tested as the base material over which the various excavated subsoils and nutrient rich topsoils will be placed, creating the reclamation profile. The LOS was initially a large stockpile which was then compacted and graded to form the base of the ASCS. Due to the variability in the PHC concentration of LOS and random spread of the LOS stockpile, there is a large spatial variability in the PHC concentration of the LOS across the area of the ASCS. Furthermore, due to compaction factors such as the non-uniform movement of machinery that has occurred on the LOS, there is also a spatial variability in bulk density. Therefore, it is important to not only understand how a uniform LOS will affect the hydraulic properties in the overlying soil profile, but also how the performance of the reclamation cover will change across the landscape as the physical properties of LOS changes.

### 1.3 Hypothesis and Objectives

It is hypothesized that due to the nature of how PHCs occupy the LOS, which will be discussed in a later portion of this document, the placement of LOS as the base layer of soil will act as a barrier of flow to the movement of subsurface water, resulting in an increased water and nutrient retention in the overlying soil profile. As stated above, the LOS itself varies spatially in PHC concentration and bulk density across the ASCS. Therefore, it is important to understand how a uniform LOS will affect the hydraulic dynamics in the overlying soil profile, as well as how the water storage capacity and nutrient residence time (or retention) will be affected by the changes in PHC concentration and bulk density of the LOS. Furthermore, little is known about the hydraulic properties of the LOS itself, so this thesis has two main objectives:

1. To characterize the LOS based on its hydraulic properties and determine how its hydraulic properties are affected by bulk density and PHC concentration.
2. To determine the soil water storage capacity and nutrient retention in the reclamation cover using LOS as the base soil layer.

The results from this study will lead to an increased understanding of how the hydraulic properties of LOS change with bulk density and PHC concentration. The data generated will also help determine how the soil water storage capacity and nutrient retention in the overlying soil cover are affected by varying PHC concentrations and bulk densities of the base LOS layer. This research will ultimately aid in the determination of the efficacy of using LOS as the base soil layer in reclamation. It may also help guide the placement of LOS in terms of bulk density and

PHC concentration in creating the desired ecosites required for returning the land to equivalent capabilities.

# 2.0 LITERATURE REVIEW

## 2.1 Oil Sands Reclamation

Due to the extensive disturbance that oil sands mining has on the landscape, it has been written into Alberta law that the companies holding the lease to the land which has been used as an oil production site must be returned to equivalent or better than pre-disturbance conditions (GOA, 1993). The reclamation process is an intensive and costly operation in which upwards of $114,000 per hectare has been spent on past oil sands reclamation projects (Grant et al., 2008). The failure to successfully reclaim the land can result in a 50% increase of cost over the initial reclamation costs in having to re-visit the reclamation site (Chenoweth et al., 2010). It is therefore in the best interest of oil sands companies to greatly improve the efficiency and effectiveness of their reclamation efforts in order to keep their costs at a minimum.

The natural soils that are found in the Alberta oil sands areas have the ability, based on their physical properties, to support a range of ecosites. Ecosites are differentiated mainly by their moisture regimes, as well as the nutrient retention capabilities of the soils (Beckingham et al., 1996). The variations in the water and nutrient retention characteristics in the dominantly coarse textured soils, across the landscape of the Athabasca oil sands, lead to the existence of numerous ecosites containing a variety of plant communities. This is one of the main challenges that presents itself in oil sands reclamation, since the soil conditions that are needed in order to achieve a desired ecosite can be quite specific. Zettl et al (2011) conducted a field study on a variety of natural sites in the Athabasca oil sands, and reported three different ecosites ("a", "b", and "d"), associated with three different moisture regimes (subxeric, submesic, and mesic, respectively), and two nutrient regimes (poor for the a ecosite and medium for the b and d ecosites). In addition, they stated that each ecosite had subdivisions for the type of plant community that was present. This goes to show the variability that these naturally occurring, coarse textured soils are able to support, and reinforces the importance of understanding how physical soil properties affect the water and nutrient dynamics.

A study by Kelln et al. (2009) outlines the importance of taking a multi-disciplinary approach to reclaiming oil sands disturbed land. This multi-disciplinary reclamation approach would need to cover a range of topics such as soil (water and nutrients), vegetation, wetlands, landscape, hydrocarbons and contaminant transport, among many others. There have been various oil sands reclamation studies looking at landscape creation (Johnson and Miyanishi, 2008; Price et al., 2010), forest vegetation (Mackenzie and Naeth, 2010; Trites, 2009b; Shaughnessy, 2010), wetlands (Rooney and Bayley, 2011), soil water and nutrients (Leatherdale et al., 2012; Naeth et al., 2011; Hemstock et al., 2010) and hydrocarbons/contaminant transport (Fleming, 2012; Visser, 2008). Many of these reclamation aspects are being studied at the ASCS however, the following research will be focused on how petroleum hydrocarbons influence the hydraulic parameters in the base LOS soil layer of the reclaimed landscape and in turn, influence the water dynamics in the overlying reclamation cover. Therefore, it is important to investigate any current understanding of how soil physical properties affect water and nutrient dynamics as well as how PHCs can be expected to influence the results in the experiments to follow.

## 2.2 Reclamation Soil Properties

### 2.2.1 Soil Texture

One component of this study is to determine how the varying physical properties of LOS (bulk density and texture) will influence the LOS's hydraulic properties and how this will, in turn, affect the water dynamics in the overlying reclamation soil profile. The effects that bulk density and texture have in soils which are not impregnated with hydrocarbons is well documented. It is important to understand these relationships in order to determine if and how PHCs influence them. Soil texture plays a major role in the infiltration of water into the soil as well as the flow of water through the soil (Hillel, 1998). Coarse textured soils, such as the reclamation soils found at the ASCS, including LOS, tend to have higher rates of water infiltration compared to finer textured soils (Leatherdale et al., 2012). Coarse textured soils also tend to have higher saturated hydraulic conductivities ($K_s$) than finer soils (Leatherdale et al., 2010). Soils with higher $K_s$ do not retain water as well as finer textured soils with a lower $K_s$, leading to lower water holding capacity in coarse textured soils (Leatherdale et al., 2012). The coarse textured soils that are available for reclamation make it challenging to successfully reclaim disturbed land. Due to the low water retention of these soils, the establishment and growth of plants can be affected, since there is inadequate plant available water. Therefore, it is important to implement reclamation practices that will help overcome the challenges faced with using coarse textured reclamation soils.

### 2.2.2 Soil Layering

One example of a reclamation practice that can increase soil water storage in the profile is implementing a soil layering system, which takes advantage of the varying soil properties in each layer to achieve the desired soil conditions. Soils form over thousands of years through translocation processes (Phillips, 2001), which results in the naturally occurring layering of soil horizons rather than one homogenous layer of soil (Huang et al., 2011). The natural layering of the coarse textured soils found in the Alberta oil sands provides a range of soil water content conditions which can support a variety of ecosites. It has been found that contrasts in soil texture throughout the profile will increase the soil water storage of these coarse textured soils, at field capacity (Zettl et al., 2010).

Textural layering of soils creates breaks in the hydraulic properties of the soil at the layer interface. This can reduce the movement of water and nutrients across the layer interface as well as reduce the flow of contaminants into groundwater (Si et al., 2011; Huang et al., 2011; Naeth et al., 2011). The breaks in hydraulic properties of soil can occur when a finer textured soil overlies a coarser textured soil, called a capillary barrier, or when a coarser texture soil overlies a finer textured soil, called a hydraulic barrier. Stormont and Anderson (1999) explain that a capillary barrier can only be present in unsaturated soils. Water will accumulate in the overlying finer textured soil where it is held at high tension, and will only flow into the underlying coarser soil when the water content becomes high enough to cause a drop in tension, allowing the water to be released (Naeth et al., 2011 and Stormont and Anderson, 1999). As the water content reaches a point that the hydraulic conductivities of each layer are close enough, the effects of the capillary barrier are negated. In addition to a capillary barrier, the hydraulic barrier is controlled mainly by the contrast in hydraulic conductivities of the overlying coarser textured soil compared to the underlying finer textured soil. Water will infiltrate more rapidly through the coarser textured soil until it reaches the finer textured soil, where the rate of infiltration will decrease in the overlying profile to the rate of the underlying finer textured soil (Si et al., 2011). Thus, the water in the profile will have a longer residence time compared to what it would be in a soil with a higher infiltration rate (Si et al., 2011).

The effect of textural breaks are evident from the occurrence of the variety of plant communities that can be found in coarse textured soils, for example jack pine or spruce and aspen stands which thrive in drier and more moist conditions, respectively. It is difficult, however, to perfectly replicate natural conditions that have developed over thousands of years. Therefore, it may be necessary to influence other soil properties within the soil layers in order to create the conditions that are required for the soil to retain the optimal amount of water for the desired ecosite.

### 2.2.3 Soil Bulk Density

Bulk density is another soil property that affects the water retention in the soil profile as it controls how easily water flows through the soil. As bulk density changes, so does the porosity of the soil (Dec et al., 2008) resulting in a change of the soil's water holding capacity. As bulk density increases, the macropores are largely affected, and the total soil porosity decreases (Dec et al., 2008). In addition, Tuli et al. (2005) found that disturbed or repacked soil samples showed a lack of macropores compared to undisturbed, structured samples. It should be noted that the LOS at the ASCS has all been disturbed as it has been excavated and stockpiled, and artificially packed into soil cores for the purposes of this study. Soil macropores are the pores that conduct soil water, so a coarse textured soil with a large proportion of macropores would have a higher $K_s$ than a finer textured soil with less macropores. Although macropores need to be present, only continuous, interconnected pores conduct water and influence the $K_s$ of that soil (Dec et al., 2008 and Bodhinayake and Si, 2004). In reclamation, if a reconstructed soil profile with varying coarse textured layers does not retain sufficient amounts of water, it is possible for the base soil layer such as LOS to be compacted to a higher bulk density which will impede the downward flow of water through the profile. Furthermore, if the pores of the base soil layer are occupied by PHCs as Mossop (1980) suggests, rather than water, this may interrupt the continuity of the connecting pores and further reduce the $K_s$, resulting in more water storage in the root zone. The combined use of soil properties such as texture and bulk density with methods like layering needs to be applied to obtain the soil conditions required in order to create target ecosites. While the effects of texture and bulk density are well known in numerous soil types, the effects of these physical properties in soils impregnated with PHCs, such as LOS, are not understood.

### 2.3 Lean oil sand

Lean oil sand is considered overburden material (Hemstock et al., 2010), and is a mixture of the rich oil sand and the overlying cretaceous shale (Kelln et al., 2008). The mixing of these soils is what gives the LOS its heterogeneity in PHC concentration. The relatively low PHC concentration of LOS, which is below 8% by weight (Visser, 2008), results in the hydrocarbon extraction process being uneconomical (Chapman et al., 2006). The LOS is therefore stockpiled until it can be used in the reclamation process, or used in the construction of dykes which are used for containing tailings (Gosselin et al., 2010). At the time of reclamation, the LOS will be levelled and contoured to the specifications of the desired landscape. This will then act as the base material over which relatively more nutrient rich subsoils and topsoils will be placed.

#### 2.3.1 PHCs in LOS

There is a limited amount of studies examining LOS, and they have primarily looked at the toxicity and transport of PHCs from LOS and the effect on environmental receptors. In thesis research conducted by Fleming (2012) on the toxicity and mobility of PHCs in tarballs taken from the Athabasca oil sands, it was found that the PHCs in tarballs, much like LOS, primarily consisted of the heavier F3 and F4 fractions. In Fleming’s study, he found insignificant amounts of PHCs in the leachate. The PHCs present in the leachate were dominated by F2 fractions, likely produced by microbial activity breaking down the heavier PHCs. Likewise, Visser (2008) found that during the time of stockpiling, the LOS experiences microbial degradation, volatilization and weathering of the lighter fractions of PHCs leaving only trace amounts of the F1 (0.15%) and F2 (8.6%) hydrocarbon fractions. The remaining PHCs are dominated by the heavier fractions (38% F3 hydrocarbons and 54% F4 hydrocarbons) (Visser, 2011). Leskiw (2005) found similar results examining shallow oil sands where F1 and F2 PHCs were insignificant and the F3 and F4 PHCs were of most concern since they exceeded the Canadian Council of Ministers of the Environment (CCME) limits. Visser (2008) found that the weathering of LOS for approximately four months removed or reduced toxic PHCs in the F2 and F3 fractions. Based on this, Visser (2008) recommended that LOS should be weathered for an extended period of time prior to placement for reclamation purposes in order to reduce the toxic effects of fresh PHCs on environmental receptors. Prior to placement for reclamation, the LOS used at the ASCS had been stockpiled and exposed to the elements for several months to years, which should be sufficient time for PHCs to weather and degrade to less toxic forms.

Kelln et al. (2008) studied the spatial distribution of soil water content in reclaimed landscapes in the northern boreal forest region. The presence of a LOS lens at upper and mid-slope locations in these reclamation profiles was found to create drier conditions in the soil overlying the LOS due to subsurface flow down the slope of the LOS (Kelln et al., 2008). Furthermore, it was found that at lower slope positions where the topography of the LOS was more flat, parts of the cover that were underlain by LOS were poorly drained (Kelln et al., 2008). This suggests that, although Kelln et al. (2008) estimated the hydraulic conductivity of the LOS layer to be similar to the cover, the LOS had a lower permeability than the overlying reclamation soil, and water would not readily penetrate the LOS layer. These results also imply that in conditions where the LOS layer below the reclamation cover has little or no slope, water will likely be held in the overlying soil profile longer than if there was no LOS present. Furthermore, Paragon Soil and Environmental Consulting Inc. (2006) observed that soil profiles which lie just above a layer containing PHCs tended to be wetter than the surrounding soil, and they speculated that there is potential for increased soil water availability if this PHC layer occurred below the root zone, within the subsoil layer.

Kelln et al. (2008) found that where there was the presence of a LOS layer in the soil, the hydrological response in the overlying soil profile varied spatially. The heterogeneity of PHC concentration and bulk density in the LOS lens was not known in the study by Kelln et al. (2008) and it is likely that this was the cause of the spatial variability in the hydrological properties in the overlying reclamation cover. Since there is limited information on these hydrocarbon layers in the soils of the boreal forest (Paragon Soil and Environmental Consulting Inc., 2006), more research is needed to explore how these hydrocarbon affected soil layers will affect the water dynamics in the soil profile, especially for purposes of reclamation. Studies looking at the heterogeneity of LOS and how it affects the hydraulic dynamics in overlying reclamation covers are needed in order to understand and model these processes.

### 2.3.2 Organic matter in lean oil sand

Petroleum hydrocarbons are organic compounds similar to the detritus that makes up soil organic matter in the way that both are composed of carbon chains (Atlas, 1981; Sollins et al., 1996). According to Strausz and Lown (2003), PHCs are composed of a range of organic compounds from volatile short-chained molecules (e.g. methane) to molecules with molecular weights exceeding 15000. Leahy and Colwell (1990) explain that PHCs undergo microbial degradation with microbes more readily degrading aliphatic and light aromatics. This preferential degradation by microbes leaves larger organic molecules such as high molecular weight aromatics, resins, and asphaltenes, which give bitumen its viscosity (Strausz and Lown, 2003). The end product of these microbial degraded PHCs (which consist of the more recalcitrant, larger chained, heavier organic molecules) is the bitumen found in the Athabasca oil sands (Strausz and Lown, 2003), which LOS is partly composed of. This is consistent with the findings from Visser (2008) stating that the PHCs found in LOS consisted mainly of the longer chained F3 and F4 fractions.

In contrast, soil organic matter in the form of plant litter is mainly composed of polysaccharides and lignin (Kogel-Knaber, 2001), and may have different effects on soil properties than PHCs due to its physical form. The LFH layer in forest soils, such as those that are found in the Alberta oil sands, exist at various stages of decomposition. Gosselin et al. (2010) explains that the L, F, and H layers represent different levels of decomposition. The L (leaf) layer is the least decomposed and the organic components are the most recognizable (Soil Classification Working Group, 1998). The F (fibric) layer is made up of partly decomposed organic matter (Soil Classification Working Group, 1998). Finally, the H (humic) layer is the most decomposed and the original organic structures cannot be recognized (Soil Classification Working Group, 1998). The humic organic layer would be most physically similar to bitumen due to its level of decomposition.

The presence of a humic layer has been shown to improve soil structure as well as increase soil water content (Piccolo, 1996). Furthermore, the addition of organic matter in soils has been shown to significantly increase the water holding capacity (Ohu, et al. 1994), especially in coarse textured soils (Bouyoucos, 1938; Bauer and Black, 1992) such as LOS. This increased water holding capacity in the soil can be attributed to a rise in soil porosity resulting from the higher organic matter content (Hudson, 1994; Walczak et al., 2002). It could be expected then that PHCs would also increase water storage in the soil. However, Mossop (1980) explains that PHCs fill the pores of the soil, whereas Wershaw (1993) states that humus coats the individual soil particles. In most cases, organic carbon is considered a surrogate for organic matter, but is not appropriate for soils dominated by hydrocarbons (e.g LOS) when being used as reclamation materials (Gosselin et al., 2010). The bitumen in the soil pores is immobile and the presence of the bitumen inhibits the flow of fluids through the porous medium (Mossop, 1980). Typically, pore space in soil is filled with air or water therefore, the porosity of the soil is not said to be reduced. Rather, the water is replacing air in the available pore space of the soil. However, an immobile substance such as PHCs in soil would act more like a solid and effectively reduce the pore space available for water to occupy and flow through (Figure B1). Therefore, for the purposes of this study, when PHCs fill the pores of oil sands, they are said to be reducing the porosity of the soil. This would result in less pore space for water to occupy and consequently, less water for plant roots to access. In the case of LOS however, it is uncertain if the low amounts of PHCs will have any effect on the hydraulic properties of the soil.

### 2.4 Experimental and Statistical Analysis

There are numerous methods that can be applied to test the various soil properties being examined in these studies therefore, it is important to select the most appropriate methods.

#### 2.4.1 Saturated Hydraulic Conductivity ($K_s$)

Saturated hydraulic conductivity can be measured in undisturbed field soils in situ, or in disturbed soil cores in the lab. Measuring $K_s$ in the field is intended to more accurately test the field conditions, as the soil is not disturbed and the structure and porosity of the soil is conserved. Measuring $K_s$ using soil cores taken from the field may disturb the structure of the soil leading to measurements that are not accurate to field conditions. Re-packed soil samples, with soil taken from the field completely disturbs the soil structure, and does not maintain the exact bulk density of field conditions. Even though the soil can be packed to specific bulk densities, the pore distribution of the soil will not be the same as undisturbed samples (Tuli et al., 2005). Since the soils being tested in these studies (LOS) have already been disturbed in the excavation process, and are coarse textured with weak or no structure, packing soil cores will not further destroy the in-situ structure that the soil possessed, when packing to different bulk densities. Reynolds et al. (2002) lists a variety of in lab techniques that can be used for measuring the $K_s$ of soils packed in cores including the constant head, falling head, and steady flow methods. Reynolds et al. (2002) explain that the constant head method is useful for measuring soils with larger $K_s$ whereas, the falling head method is best for finer textured soils with lower $K_s$. The steady flow method can be used to measure all soil types however, it is particularly useful in measuring clay soils that swell with increasing water content (Reynolds et al., 2002). The constant head method was determined to be the most appropriate technique to measure $K_s$ of the LOS due to its coarse texture.

### 2.4.2 Soil Water Retention Curves

Soil water retention curves relate the soil suction to the volumetric water content of a soil. These curves allow the determination of how soil retains water at varying suctions and under conditions such as field capacity and permanent wilting point (PWP). There are numerous methods that can be used to determine the water retention curves for soil. Depending on the type of soil that is being tested in terms of structure and texture, as well as how many samples need to be analyzed, one method might be better suited than another. A hanging water column is suitable for up to 200 cm of suction however, only one sample can be analyzed at a time (Dane and

Hopmans, 2002). A pressure cell will test the water retention curve at higher suctions (up to 850 cm), but it also can only measure one sample at a time (Dane and Hopmans, 2002). A long column can be used to take point measurements of water content at suctions of less than 100 cm throughout the profile (Dane and Hopmans, 2002). The wetting curve of soils can be tested in addition to the drying curve using the controlled liquid volume method (Winfield and Nimmo, 2002). This method reduces equilibration times in the soil however, it is also limited by the number of samples that can be analyzed at one time. Since there were multiple samples to be analyzed in this study, methods that could accommodate numerous samples at once needed to be utilized. For pressures under 100 cm of suction, a tension table was used since it can process multiple samples and has a relatively low cost (Dane and Hopmans, 2002). Pressure plates were used for the pressures greater than 100 cm and up to 15000 cm. Pressure plates also have the capacity to analyze multiple samples at once. One limitation to the chosen methods is the long equilibration times that can occur, especially for larger soil cores.

#### 2.4.2.1 Curve Fitting

The water retention curve is one of the most fundamental hydraulic characteristics of a soil however, it is very time consuming to measure (Assouline et al., 1998). In order to make the determination of the water retention curve less time consuming and tedious, many attempts have been made to come up with a mathematical function that will relate the volumetric water content to the soil suction and accurately fit the water retention curve using only a few, easily measured soil parameters. Kosugi et al. (2002) lists some of the most widely used functions that fit the water retention curve including ones by Brooks and Corey (1964), Brutsaert (1966), van Genuchten (1980), and Russo (1988), to list a few. Many of the functions are slightly re-worked versions of previous functions, in the attempt at making them more versatile and accurate. The van Genuchten (1980) function was chosen for the curve fitting in this study. The van Genuchten (1980) function was chosen because it is among the most used and widely accepted functions for fitting the water retention curve (Kosugi et al., 2002; Assouline and Tartakaovsky, 2001; Porebska et al., 2006). A few studies (Nimmo, 1991; Ross et al., 1991) have shown that the van Genuchten (1980) model is not very accurate at low water contents (high suctions). Since it is unclear as to how the PHCs in the LOS will influence the hydraulic properties of the LOS, it was important to choose a model that can handle a wide range of conditions and soil parameters. Vereecken et al. (1989) found that the van Genuchten model not only performed well over the entire range of the water retention curve, but that it was also flexible for modelling a wide range of soil textures. The ability of this model to fit well with a wide range of soil textures as well as its extensive use throughout literature resulted in providing a desired fit for the data in this study.

### 2.5 Summary

Since mine development in the Alberta oil sands began, there has been a need for soil reclamation of the disturbed land. Over the years, the scale of land disturbance in the Alberta oil sands has grown immensely and is continuously increasing. To date, only a very small fraction of disturbed land has been certified reclaimed, meaning the leased land has been handed back to the crown as public land, even though government requires companies to reclaim the land that they have disturbed. This has led to an increase in land reclamation studies of all types, and a large body of accumulated knowledge on the reclamation of oil sands disturbed land. From the available literature on oil sands reclamation, there are relatively limited studies specifically on hydrocarbons in the soil. Of the few studies on hydrocarbons in reclamation soils, the majority of them look at the potential contamination due to the presence and movement of PHCs in the profile. There is however, a very limited amount of studies looking at the physical presence of

PHCs in the reclamation soils in the Athabasca oil sands. To the author's knowledge, none of the studies on hydrocarbons look at how the PHCs affect the water dynamics of the LOS. Furthermore, the knowledge gap on this subject extends to how the presence of PHCs in the base reclamation layer will affect the hydraulic properties in the overlying profile.

The reclamation soils used at the ASCS are predominantly coarse textured, and there is a range of ecosites with varying moisture regimes that need to be replicated for reclamation success. Soil reclamation methods such as layering need to be employed in the attempt to re-create the specific ecosites. Sometimes, due to the coarse textured nature of available reclamation soils, the existing reclamation methods may not be enough to achieve the desired soil moisture regimes. The need for additional methods to control the water content in the soil profile, such as the inclusion of the base LOS layer with varying PHC concentration may be required. The following research takes this into consideration and begins to close the knowledge gap in the literature regarding how PHCs in LOS affect the water dynamics in LOS, as well as how the overlying soil profile is affected. The knowledge obtained from this research will aid in the placement of LOS in reclamation, and improves the understanding of how PHCs affect the hydraulic properties of soil.

# 3.0 Effects Of Petroleum Hydrocarbon Concentration And Bulk Density On The Hydraulic Properties Of Lean Oil Sand Overburden

## 3.1 Preface

The success of soil reclamation relies on the ability to recreate soil profiles that will retain sufficient water and nutrients required to support vegetative growth and stability. This can be a challenge in the Alberta oil sands as some of the soils that are available for reclamation are coarse textured and have poor water retention. Lean oil sand (LOS) is an overburden material that is being tested as the base soil layer on which the coarse textured reclamation soils are placed. Relatively small amounts of petroleum hydrocarbons (PHCs) are present in LOS and little is known on the effects that PHCs have on the hydraulic properties of soils. In addition, during the placement of LOS as the base soil layer, in preparation for cover soils to be placed, the non-uniform movement of heavy machinery creates variability in the bulk density of the LOS. In order to understand how LOS as the base soil layer will affect reclamation success, it is important to have an understanding of how the hydraulic properties of LOS changes as PHC concentration and bulk density changes. The following research study looks at the effects of PHC concentration and bulk density on the hydraulic properties of LOS.

### 3.2 Introduction

The second largest oil reserve in the world is contained within the boreal forest of Northern Alberta and is known as the Alberta oil sands (GOA, 2009). The Alberta oil sands consist of three separate petroleum hydrocarbon (PHC) rich deposits referred to as the Peace River, Cold Lake, and Athabasca deposits (Johnson and Miyanishi, 2008). Together, these oil sand deposits cover an area of 140,000 $km^2$ with projected development areas encompassing more than 480,000 hectares of land (Johnson and Miyanishi, 2008; GOA, 1993). In the oil sand mining process, the organic peat or topsoil, glacial subsurface soils (alluvial, lacustrine or till), and overburden soils (saline-sodic shale or lean oil sands) are excavated and stockpiled prior to mining the oil sands ore. The lean oil sands (LOS) are sands that contain naturally-ocurring PHC concentrations of 0 to 8% by weight (Visser, 2008). With current technology and extraction methods, it is not economically viable for companies to extract the low amounts of oil from LOS. The surficial organic and glacial subsurface soils are used to construct reclamation soil covers while the overburden soils are placed in large dumps which are subsequently reclaimed. According to the Environmental Protection and Enhancement Act of Alberta, land that has been used as an oil production site must be returned to an equivalent land capability similar to what it was prior to being used as an oil production site. This requires that reclaimed land be returned to the same or similar type of ecosite that was present prior to the disturbance. Ecosite types are defined primarily on the basis of nutrient and soil moisture availability (Beckingham et al., 1996).

Syncrude Canada Ltd. has developed a long-term, instrumented watershed research site on a predominantly LOS overburden dump. The research site is located on the Fort Hills dump at

Syncrude's Aurora North mine, approximately 50 km north of Fort McMurray, Alberta (57º19'20"N, 111º30'24"W) (Figure 3.1).


**Figure 3.1.** Map of the Alberta oil sands and the approximate location of Syncrude's Aurora North Mine. (http://oilsands.alberta.ca/resource.html), and aerial photograph of the ASCS.

This research site is referred to as the Soil Aurora Capping Study (ASCS). The purpose of the study is to test the efficacy of various reclamation material types, placement configurations and depths over LOS overburden to return the disturbed land to equivalent land capability. The LOS at the ASCS was initially a large overburden dump which was graded to create a landform that is geotechnically stable and has integrated surface water drainage. Due to inherent variability of PHC concentration in LOS and the use of large equipment to move and spread the material to its designated location, there is a spatial variability of PHC concentration and compaction throughout the entire area of lean oil sand on the Aurora Soil Capping Study.

Visser (2011) reported that LOS contains trace amounts of hydrocarbons in the F1 (Carbon [C] chain 6-10) and F2 (C10-16) fractions and 38% and 54% in the F3 (C16-34) and F4 (C>34) fractions. The LOS selected at the ASCS not only varied in organic carbon content (or PHC concentration), but also varied in sand, silt, and clay content. Texture analysis of LOS samples from the ASCS returned an average texture of sandy loam, with proportions of 55 to 60% sand, 30% silt and 10 to 15% clay (NorthWind Land Resources Inc., 2013). Although the effects that soil properties such as organic matter, texture, and bulk density have on soils is well known, there is limited information on the effect of PHCs on soil hydraulic properties. Increased clay and organic carbon in soil can act as aggregating agents, increasing the water holding capacity by improving soil structure and increasing porosity (Nimmo, 2004; Tisdal and Oades 1982). Increases in bulk density reduce soil porosity, which in turn reduces the overall soil water storage and saturated hydraulic conductivity (Dec et al., 2008). Due to the lack of understanding of how organics in the form of PHCs affect soil hydraulic properties, it is important to explore their effects on soil hydraulic properties as well as any effects resulting from their interactions with other soil physical properties such as bulk density or texture.

The objective of this study was to characterize the hydraulic properties, specifically saturated hydraulic conductivity (Ks) and water retention curves of LOS, to determine how its hydraulic properties are affected by bulk density and PHC concentration. The results are intended to help determine the effect of a LOS base material on soil-water retention and release in the overlying reclamation profile. The results of this study have implications to selecting soil cover designs that provide an adequate amount of water for the vegetated ecosystem targeted for closure.

## 3.3 Materials and Methods

The LOS was collected directly from the ASCS after the site had been graded, contoured, and was ready for reclamation soil placement. Several samples of LOS were collected from two different areas of the ASCS for the purpose of obtaining LOS with a range of PHC concentrations. Prior sampling and laboratory analysis of the ASCS delineated PHC concentrations across the site and was used to select sample locations which covered a range of PHCs, one area with PHCs from 5 to 7% and a second area with PHCs of 2 to 4%. The LOS samples were shipped to the University of Saskatchewan (U of S) to be processed. The samples were air dried on separate tarps and were well mixed to create two homogenous PHC concentration samples: a high PHC concentration soil (7.48%) and a low PHC concentration soil (3.25%). These PHC concentrations were determined by analyzing subsamples, taken from each of the two bulk samples, for organic carbon using the LECO C632 dry combustion carbonator (LECO Corp., St. Joseph, MI, USA) (Wang and Anderson, 1998). Since the LOS had very little to no soil organic matter, it was assumed that any organic carbon detected in the LOS was due to hydrocarbons.

A portion of the 7.48% LOS material was baked in a high temperature oven at 550ºC for four hours to remove all organic carbon (Heiri et al., 2001), effectively creating a LOS sample with a PHC concentration of 0%. Mixing the two PHC concentration samples with the 0% PHC sample was undertaken to create 5 different PHC concentration samples (0%, 1.63%, 3.25%, 5.37%, and 7.48%). These samples were compacted to two different bulk density values (1.5 and 1.7 g $cm^{-3}$) which encompass the approximate range that can be found within the surface 30 cm of LOS at the ASCS. The combination of five PHC concentration LOS soils and two bulk densities resulted in a total of 10 different treatments. The treatments were replicated five times (n=5) in the study.

In addition to the PHC analysis, particle size analysis (PSA) was conducted on samples of LOS for the five PHC concentrations using the Horiba LA-950 particle size analyzer (Horiba Scientific, Edison, NJ, USA). Each sample was filtered through a 2 mm soil sieve prior to the PSA test.

Fifty copper soil cores with a length and inner diameter of 5.08 cm were packed with LOS at the two bulk densities and five PHC concentrations, with five replicates. Prior to packing the cores, the LOS was sieved through a 4.75 mm soil sieve to remove any large aggregates or rocks. The LOS was then wetted to 5% gravimetric water content using de-aired water amended with 0.005M $CaSO_4$ (Dane and Topp, 2002). The addition of water assisted the packing of the samples to specific densities and reduced soil layering. The cores were then packed with the LOS by stacking two cores on each other, pouring the required amount of soil for the specific density into the cores and compressing until the soil was level with the top of the bottom core (Klute, 1986).

To test the water retention curves for the LOS, the cores were first saturated with a .005 M $CaSO_4$ solution of de-aired water. The cores were saturated from the bottom by placing them into containers with a layer of de-aired, distilled, 0.005M $CaSO_4$, $H_2O$ solution for a minimum of 48 hours. The cores were then placed on a suction table for the lower tensions (up to 70 cm) and pressure chambers for the higher tensions (100 cm to 15000 cm). The method and design for the suction table was described by Dane and Topp (2002). The silt/clay liner used in the suction table was 60% silt and 40% clay instead of the suggested 50/50, because it was found that more clay resulted in shrinkage and cracking in the liner at lower moisture contents.

Air can become entrapped in some of the soil pores during saturation, and this entrapped air can affect the hydraulic properties of the soil such as the water retention curve and saturated hydraulic conductivity (Faybishenko, 1995). Faybishenko (1995) found that saturating the soil under vacuum pressure or first saturating with $CO_2$ will reduce the air entrapment to 0.1-0.2%. This was felt unnecessary however as Faybishenko (1995) also found that saturating soil cores from the bottom results in less than 5% air entrapment, and the occurrence of some air entrapment would more closely represent conditions found in the field.

The saturated weight of each core was recorded prior to placement on the suction tables. Five tensions were tested on the suction table (3 cm, 10 cm, 30 cm, 50 cm and 70 cm). At the start of each tension, the cores were left on the suction table for one week, then weighed and placed back on the suction table. The cores were then weighed every 24 hours following the one week period until they came to hydrostatic equilibrium. Hydrostatic equilibrium is reached when the cores experience no more than 0.1 g drop in weight within a 24 hour period (Dane and Topp, 2002).

Following the suction table measurement, the cores were re-saturated to test the saturated hydraulic conductivity (Ks). The Ks was measured using vertical cores under a constant head as described by Dane and Topp (2002). A constant ponding of 2.54 cm of water was maintained on top of the vertical, saturated soil cores throughout the duration of the Ks experiment resulting in a total hydraulic head of 7.62 cm (core height (5.08 cm) + ponded water (2.54 cm)) . Each core was run for three consecutive time periods (5, 10, and 15 minutes), resulting in 30 minutes in total. The leachate from the bottom of the cores was collected and weighed in three separate dram vials corresponding with each time period. These time intervals were chosen to ensure enough time for the movement of water through the cores to reach equilibrium. Darcy's law was applied to describe the movement of water through saturated porous materials and is stated as:

$$K_s = \left(\frac{Q}{A}\right)\left(\frac{L}{h+L}\right) \tag{3.1}$$

Where $K_s$ is the saturated hydraulic conductivity (cm $s^{-1}$), $Q$ is the volume of water flowing out of the core per unit time ($cm^3$ $t^{-1}$), $A$ is the cross sectional area of the core ($cm^2$), $L$ is the height of soil column (cm) and $h$ is the height of the water head on top of the core (cm).

Following the saturated hydraulic conductivity measurement, the cores were saturated once again and placed into pressure chambers to measure water retention at higher suctions (330 cm, 5000 cm, and 15000 cm). The suction of 330 cm was used in this study to represent field capacity as Colman (1947) found that soil suction of 330 cm consistently represented field capacity in a range of soil textures. Permanent wilting point was represented by 15000 cm of soil suction as it was found that any water loss past this suction is negligible (Richards and Weaver, 1943; Veihmeyer and Hendrickson, 1950; Smith and Mullins, 2000). The re-saturated weights were recorded and pressure was applied to the cores. For the pressure equivalent to 330 cm of soil suction, 1 bar pressure plates were used. A 5 bar pressure plate was used for the 5000 cm pressure and a 15 bar pressure plate was used for the pressure of 15000 cm.

For the pressures of 5000 cm and 15000 cm of suction, the cores were subsampled and the left over soil was placed into plastic bags and into a refrigerator for storage. Smaller cores were used for these higher pressures to reduce equilibration time. The smaller cores were 1 cm tall with an inner diameter of 5 cm. A filter paper (#4 Whatman) was glued to the bottom of each core using epoxy, and the LOS was subsampled from the bags into the cores so that the soil filled the core and was level with the top of each core in order for the volume of soil to be known. The same process for weighing the cores in the suction table was applied to the cores in the pressure chambers; the cores were weighed every 24 hours after the initial one week period, until hydrostatic equilibrium was reached. Once the cores were finished at the final pressure of 15000 cm of soil suction, the soils were weighed and placed in tin weigh boats. The gravimetric water content was then measured by drying the LOS in an oven at 105ºC for 24 hours. The volumetric water content was calculated from the gravimetric water content, the mass of dry soil in the sample, and the total volume of the soil. The available water holding capacity (AWHC) was calculated as change in volumetric water content from field capacity to PWP.

The water retention curve for each treatment was fitted using the equation described by Van Genuchten (1980) which states that:

$$\theta = \theta_r + (\theta_s - \theta_r)[1/(1 + (\alpha h))]^{1-1/n} \tag{3.2}$$

where $\theta$ is the volumetric water content ($cm^3\ cm^{-3}$), $\theta_r$ is the volumetric water content ($cm^3\ cm^{-3}$) at permanent wilting point, $\theta_s$ is the saturated water content ($cm^3\ cm^{-3}$), $h$ is the pressure head (cm) and $\alpha$ and $n$ are fitting parameters.

Analysis of variance (ANOVA) and Post-hoc tests were conducted to determine whether the treatments of bulk density, PHC concentration, and their interactions had any significant effects on soil hydraulic properties. The least significant difference was used for the Post-hoc tests. The repeated measures ANOVA was used to test whether PHCs had any significant effects (between group) on soil water contents under nine suctions (within group) for each bulk density. For this purpose, both raw and normalized soil water content were tested. All of the statistical analyses were conducted using the SPSS 11.0 (SPSS Inc., Chicago, IL, USA). Treatment effects and interaction effects were considered significant when P values were < 0.05.

### 3.4 Results and Discussion

Soil texture of the samples is relatively consistent, ranging from sandy loam to loamy sand (Table 3.1). The sand and silt proportions vary among the samples, while only the 3.25% and 5.37% PHC samples contain appreciable amounts of clay (11.15% and 5.83%, respectively) relative to the other samples.

**Table 3.1.** Particle size analysis of LOS using the Horiba LA-950 particle size analyzer.

| LOS | Soil Separate (g/100 g) | | | Texture |
|---|---|---|---|---|
| (% PHC)* | Sand | Silt | Clay | |
| 0 | 84.18 | 15.82 | 0.00 | Loamy Sand |
| 1.63 | 75.25 | 24.67 | 0.08 | Loamy Sand |
| 3.25 | 54.95 | 33.90 | 11.15 | Sandy Loam |
| 5.37 | 60.05 | 34.13 | 5.83 | Sandy Loam |
| 7.48 | 73.85 | 25.98 | 0.17 | Loamy Sand |

Bulk density was shown to have significant effects on the various physical properties of the LOS. Table 3.2 displays the breakdown of porosities in the LOS at each PHC concentration and bulk density, which were calculated from the water retention curves based on soil pore diameter guidelines by Luxmoore (1981). These guidelines specify that macroporosity consists of pores that are greater than 1.0 mm in diameter and correspond to the suctions between 0.0 and 3.0 cm. Mesoporosity includes pore sizes ranging between 1.0 mm and 0.01 mm, with suctions between 3.0 cm and 300 cm. And finally Luxmoore (1981) describes micropores as the pores holding water at suctions greater than 300 cm which correspond to pore diameters less than 0.01 mm.  Over the range of PHC concentrations, the higher bulk density (1.7 g $cm^{-3}$) LOS samples, excluding the 3.25% sample, had a significantly greater volume of micropores. The microporosity in the 3.25%, high bulk density sample was not significantly higher because the low bulk density sample also had an elevated microporosity resulting from the increased clay content in the 3.25% PHC samples. An increase in bulk density had an opposite effect on the mesoporosity of the LOS samples. Across the range of PHC concentrations, an increase in bulk density significantly reduced the volume of mesopores. As the soil is compacted to a higher bulk density, a large proportion of the mesopores are compressed, resulting in a larger proportion of micropores, and a lower total porosity.

**Table 3.2.** Available water holding capacity (AWHC) and porosities of LOS at various PHC concentrations and bulk densities.

| Treatment | AWHC† ($cm^3$ $cm^{-3}$) | | Macro†(>1.0mm) | | Meso†(1.0-0.01mm) | | Micro†(<0.01mm) | | Total* | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bulk Density (g $cm^{-3}$) | | Bulk Density (g $cm^{-3}$) | | | | | | | |
| PHC (%) | 1.5 | 1.7 | 1.5 | 1.7 | 1.5 | 1.7 | 1.5 | 1.7 | 1.5 | 1.7 |
| 0 | $0.12^{a}$ | $0.15^{bcd}$ | $0.01^{a}$ | $0.00^{bc}$ | $0.22^{ac}$ | $0.13^{bf}$ | $0.21^{a}$ | $0.24^{bc}$ | 0.44 | 0.36 |
| 1.63 | $0.13^{ad}$ | $0.16^{cef}$ | $0.00^{bcd}$ | $0.00^{bd}$ | $0.23^{c}$ | $0.12^{bh}$ | $0.22^{ab}$ | $0.26^{c}$ | 0.45 | 0.34 |
| 3.25 | $0.16^{bde}$ | $0.17^{cef}$ | $0.00^{cd}$ | $0.01^{ac}$ | $0.24^{c}$ | $0.15^{f}$ | $0.23^{bd}$ | $0.24^{cd}$ | 0.47 | 0.32 |
| 5.37 | $0.13^{ad}$ | $0.17^{bf}$ | $0.00^{d}$ | $0.00^{cd}$ | $0.23^{c}$ | $0.10^{h}$ | $0.17^{e}$ | $0.22^{ab}$ | 0.40 | 0.30 |
| 7.48 | $0.11^{a}$ | $0.15^{df}$ | $0.00^{cd}$ | $0.00^{bd}$ | $0.20^{a}$ | $0.09^{h}$ | $0.14^{f}$ | $0.17^{e}$ | 0.34 | 0.27 |

†Treatments with same letters are not significantly different at P=0.05 within each of: AWHC, macroporosity, mesoporosity, and microporosity

*Total porosity calculated from the summation of the macro-, meso-, and micropores.

**Table 3.3.** Fitted or measured hydraulic parameters for different bulk density LOS soils.

| Treatment | | *Ks* (cm $h^{-1}$) Mean† | $\alpha$ ($cm^{-1}$) Mean† | *n* Mean† | $\theta r$ ($cm^3$ $cm^{-3}$) Mean† | $\theta s$ ($cm^3$ $cm^{-3}$) Mean† | $\theta fc$‡ ($cm^3$ $cm^{-3}$) Mean† |
|---|---|---|---|---|---|---|---|
| Bulk density | 1.5 | $4.88^{a}$ | $0.046^{a}$ | $1.47^{a}$ | $0.062^{a}$ | $0.420^{a}$ | $0.193^{a}$ |
| (g $cm^{-3}$) | 1.7 | $0.50^{b}$ | $0.011^{b}$ | $1.60^{b}$ | $0.068^{b}$ | $0.346^{b}$ | $0.226^{b}$ |

† Treatments are significantly different at P=0.05 with different letters.

‡ *fc* = field capacity

The water retention curves show that the LOS packed at a bulk density of 1.5 g $cm^{-3}$ (Fig. 3.2a) retains more water at saturation than the LOS packed at 1.7 g $cm^{-3}$ (Fig. 3.2b). This is due to the reduction of total porosity in the LOS available for water to occupy at the higher bulk density. Another clear trend evident for both bulk densities is the reduction of water retention as PHC concentration increases. A repeated measures ANOVA test found that PHC concentration significantly affected the water retention curves at both bulk densities. The water retention of the 5.37% and 7.48% PHC concentration samples have curves that are significantly different from each other and significantly lower than the lower PHC concentration samples. The water retention curves for the 0%, 1.63%, and 3.25% PHC concentrations are not significantly different from one another for both bulk densities.

The mean values of the fitted van Genuchten (1980) parameters for each bulk density were calculated by averaging the parameter values of the five PHC concentrations (Table 3.3). Figure 3.3 displays the various hydraulic parameters at individual PHC concentrations and bulk densities. The high bulk density LOS soil exhibits a significantly lower mean $\alpha$ value than the low bulk density LOS (Table 3.3). White and Sully (1992) and Raats (1976) explain that $\alpha$ is related to the inverse of macroscopic capillary length scale, which is related to the soil's particle size distribution. The greater volume of micropores associated with the high bulk density LOS samples (Table 3.2) are more conducive to a higher capillary rise than the low bulk density LOS, which is dominated by mesopores leading to a lower capillary rise and a higher mean $\alpha$ value (Table 3.3).

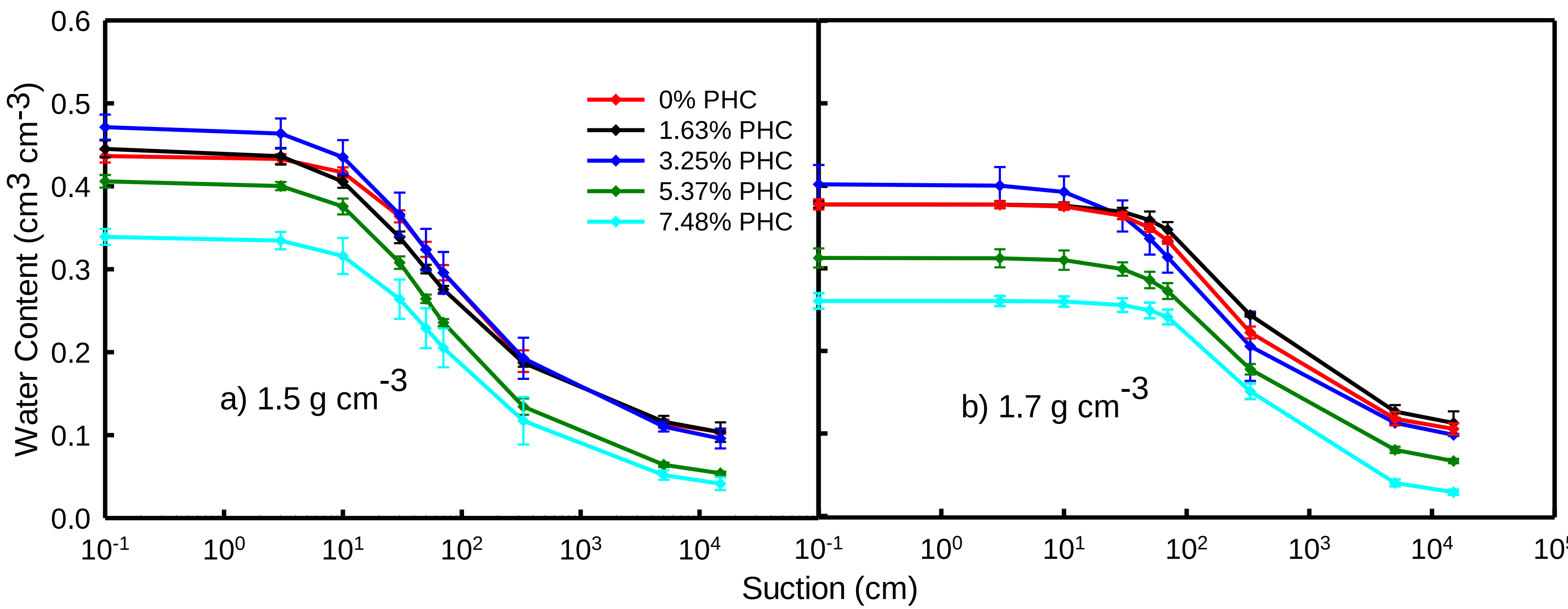


**Figure 3.2.** Water retention curves for lean oil sand (LOS) fitted using the van Genuchten equation.

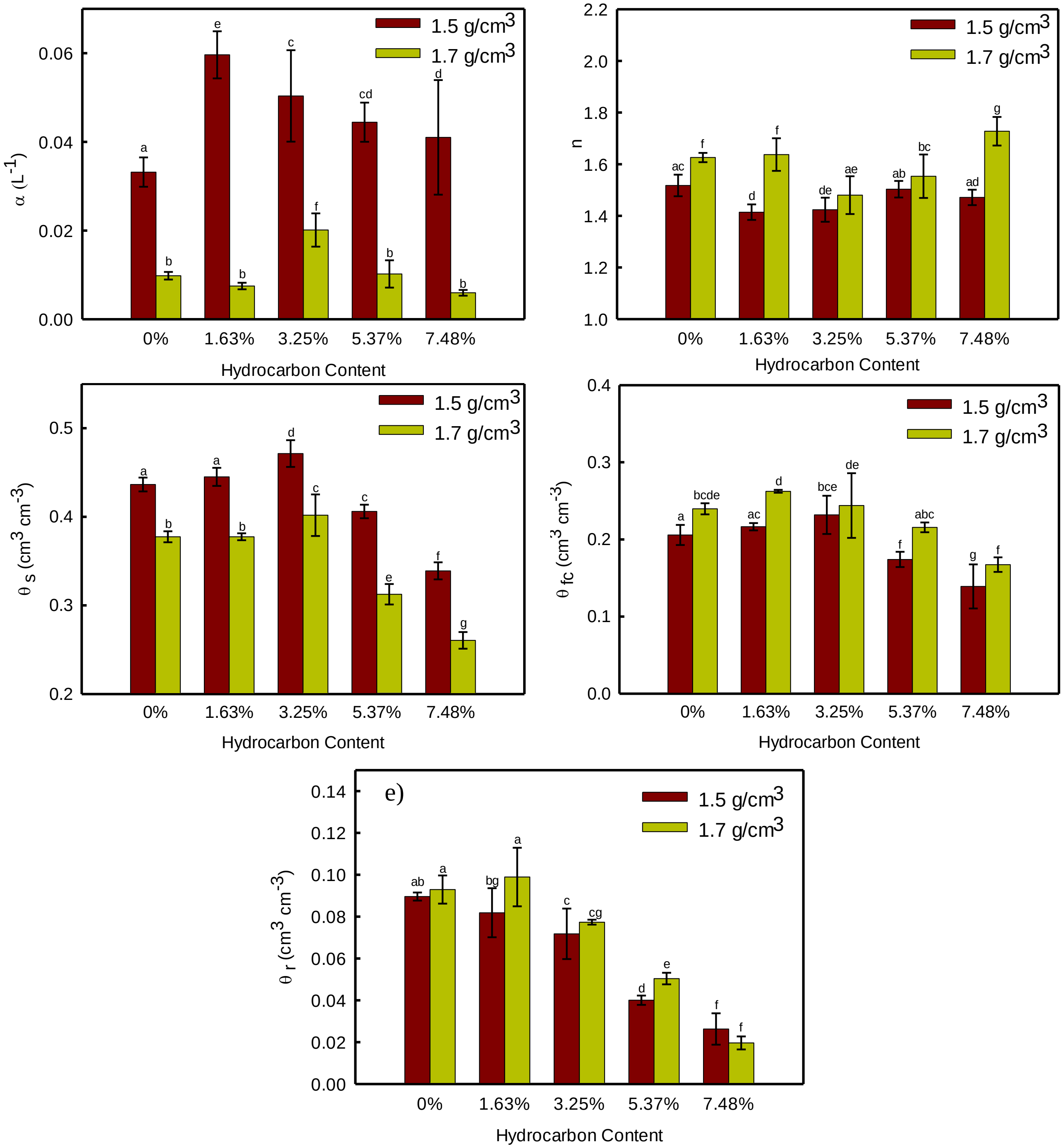


**Figure 3.3.** Various fitted and measured soil hydraulic parameters plotted as a function of hydrocarbon concentration.

The parameter $n$ is directly related to the slope of the water retention curve (van Genuchten, 1980), and a higher $n$ value corresponds with a steeper slope. As $n$ increases, there will be a larger change in soil water content at increasing suctions than a curve with a lower $n$ value. In the lower bulk density LOS, the $n$ parameter was significantly lower than at the higher bulk density (Table 3.3). As was shown in Table 3.2, the greater compaction in the high bulk density LOS reduced mesoporosity and increased microporosity, resulting in a narrower range of pore sizes and a higher $n$ parameter value. The high bulk density LOS, across the range of PHC concentrations, contains a relatively higher volume of micropores, even though the overall porosity is smaller than in the low bulk density LOS. This leads to a higher $n$ value, because as relatively more water is stored in the micropores, more water is also lost at the respective suctions, leading to a steeper slope for that part of the water retention curve.

In addition to the effects that bulk density has on the various soil hydraulic parameters, PHC concentration of the LOS also affected the soil hydraulic parameters, and these interactions are graphically represented in Figure 3.3. In order to support the analysis of the effects that PHCs have on the soil parameters (which are shown in Fig. 3.3), the normalized water content, $\Theta$, was calculated using the formula:

$$\Theta = (\theta - \theta_r)/(\theta_s - \theta_r) \tag{3.3}$$

where $\Theta$ is the normalized water content ($cm^3\ cm^{-3}$), $\theta$ is the volumetric water content ($cm^3\ cm^{-3}$) at a specific suction on the water retention curve, $\theta_s$ is the saturated water content ($cm^3\ cm^{-3}$) and $\theta_r$ is the volumetric water content ($cm^3\ cm^{-3}$) at permanent wilting point measured at 15000 cm of suction, and was graphed as a function of the suction (Fig. 3.4). ANOVA with repeated measures analysis shows that the normalized water retention curves for each LOS sample, over the range of suctions, are statistically similar to one another in their respective bulk densities, with exception given to the 3.25% and 7.48% PHC samples at the high bulk density. The soil hydraulic parameters are reflective of the shape of the water retention curve; therefore, due to the similarity between each curve, it can be concluded that even though PHC resulted in significant differences of $\alpha$ and $n$, these differences did not have a large physical effect on the soil water retention. Nevertheless, significant differences are seen between the measured water retention curves (Fig. 3.2) due to the effects of bulk density and PHC concentration on the $\theta s$ and $\theta r$ values. As was mentioned, the 3.25% PHC curve (Fig. 3.4b) is significantly different than the other PHC samples at the high bulk density. This is likely due to the elevated clay content in the high bulk density soil sample, as clay has the ability to increase aggregation (Nimmo, 2004). Since the high bulk density treatment has lower porosity than in the low bulk density treatment, the effect of aggregation due to clay can be elevated. The 7.48% PHC curve (Fig. 3.4b) is significantly different than only the 0% PHC curve, likely due to the relatively large difference in PHC concentration between the 0% and 7.48% PHC samples compared to the difference between the 7.48% and other PHC concentration samples. In addition, with the high bulk density soil treatment having a lower total porosity, an increase in PHCs occupying available pore space has a more profound effect as PHCs fill a larger proportion of the total pore space.

Figure 3.3(a) shows that there are no consistent statistical patterns in $\alpha$ that result from the effects of PHCs at each of the packing densities (Fig. 3.4). Any patterns that could have been deduced due to the effects of PHCs may have been masked by the effect of texture from the elevated clay content in the mid-ranged PHC samples. Bulk density is shown to have a larger effect on $\alpha$ than PHC concentration does. This bulk density effect can also be seen in Figure 3.4;

the air entry value is closely related to $\alpha$ (Fredlund and Xing, 1994) and, for each curve in the high bulk density samples, the air entry shifts to a higher suction than the low bulk density samples. Even though there are statistically significant variations in $\alpha$ at different PHC concentrations, the differences between the $\alpha$ values within each bulk density have no physical implications because there were no significant differences between the normalized water retention curves in Figure 3.4. In addition, all of the values fall within the same general range of texture class as shown by Carsel and Parrish (1988). The low bulk density sample's $\alpha$ values are consistent with the Carsel and Parrish (1988) $\alpha$ values and represent a loam to sandy clay loam. The same holds true for the high bulk density sample's $\alpha$ values, as they lie within the Carsel and Parrish (1988) range of a silty clay loam to sandy clay loam textured soil.

Figure 3.3(b) shows the relationship between the $n$ parameter at each bulk density and PHC concentration. Much like the results for the $\alpha$ values, there could be no deduction of statistical trends in $n$ resulting from the effects of PHC concentration. Clay content once again, had a statistically noticeable effect that masked any possible trends that PHCs could have on $n$. Based on ANOVA with repeated measures analysis, and shown in Figure 3.4, the physical effects of any change in $n$ are minimal in this LOS material. Consequently, in their respective bulk densities, all $n$ values lie within the range that corresponds with similar soil textures, as presented by Carsel and Parrish (1988). The $n$ values for the low bulk density samples fall in the soil textural range of loam to silt and the high bulk density samples fall in the range of $n$ values which are representative of a loam to sandy clay loam (Carsel and Parrish, 1998).

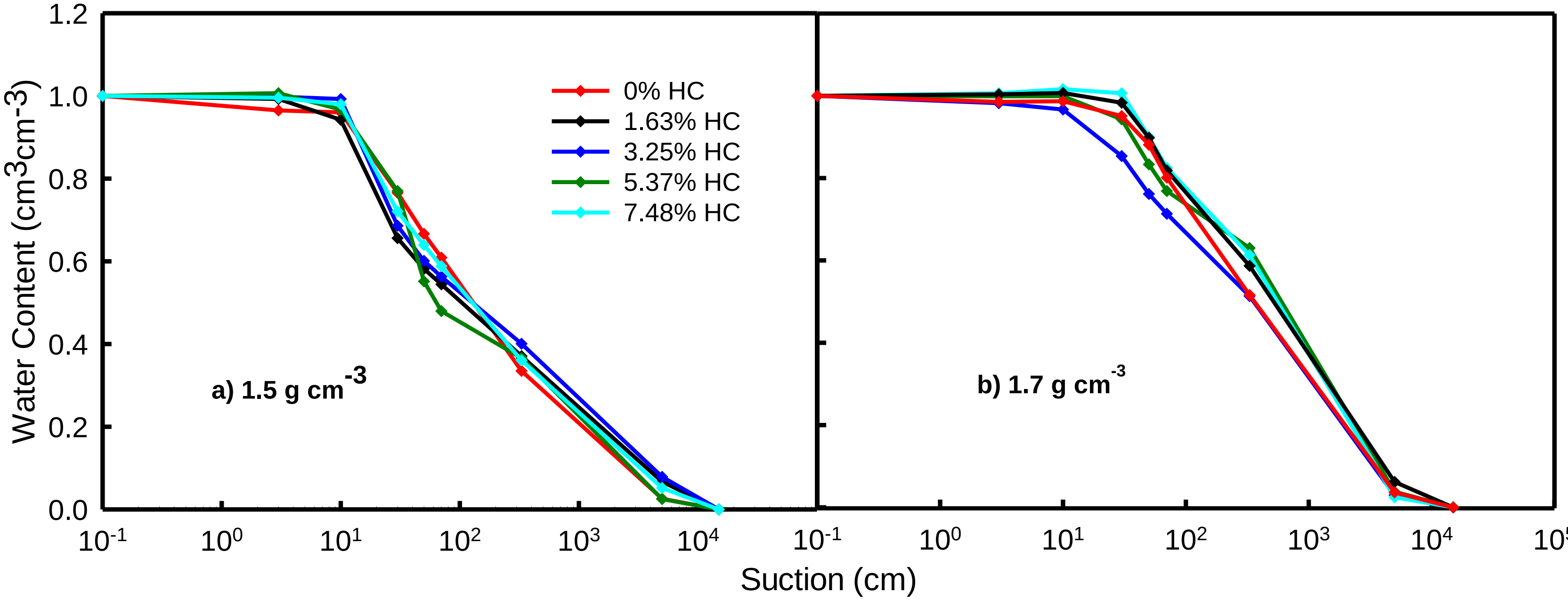


**Figure 3.4.** Normalized water content graphed as a function of soil suction.

Figure 3.3(c) shows the $\theta_s$ of LOS packed at both bulk densities and varying PHC concentrations. The high bulk density LOS has a significantly lower $\theta_s$ than the low bulk density LOS (Table 3.3) which is due to a lower total porosity. Comparing the LOS at the varying PHC concentrations, the $\theta_s$ in both bulk densities gradually increases from 0% to 1.63% PHC with a significant increase to the 3.25% PHC sample. Table 3.1 shows that the LOS with 3.25% PHC has a higher clay content (11.15%) than the 0% and 1.63% LOS (0% and 0.08%, respectively). Higher clay content means relatively lower sand content, but can increase aggregation, resulting in more pores for storing soil water therefore, the observed increase in $\theta_s$ of the 3.25% PHC sample is likely attributed to the elevated clay content and surface area, which is consistent with other literature (Gupta and Larson, 1979). This increase in the $\theta_s$ of the 3.25% PHC samples relative to the other PHC samples can be seen in Figure 3.5. Figure 3.5 shows the calculated total porosity of the LOS, which accounts for the loss of porosity due to the volume of PHCs present, graphed as a function of the measured total porosity of LOS ($\theta_s$). The points representing the 3.25% PHC samples in both bulk densities lie the furthest away from the 1:1 line, whereas all of the other points are scattered close to the 1:1 line. The points in figure 3.5, which lie close to the 1:1 line represent the $\theta_s$ being similar to the calculated total porosity of the LOS. The increase in the measured porosity of the 3.25% LOS in relation to the theoretical or calculated porosity is due to the samples' elevated clay content. As the PHC concentration increases to 5.37% and 7.48%, the $\theta_s$ drops significantly in both bulk density samples. At these higher PHC concentrations, the PHCs are filling more soil pore space that would otherwise be occupied by water. Note that the 5.37% PHC LOS also has an appreciable amount of clay (5.83%) relative to the lower PHC concentrations with no clay (<0.1%), yet the $\theta_s$ is still lower in the 5.37% PHC samples. This suggests that there may be a threshold value for PHC concentration of around

3.25%, over which the water reducing effects of PHC concentration become significant, as compared to below 3.25% PHC, the effects of PHCs filling pores are not significant and other properties such as clay content have more of an impact.

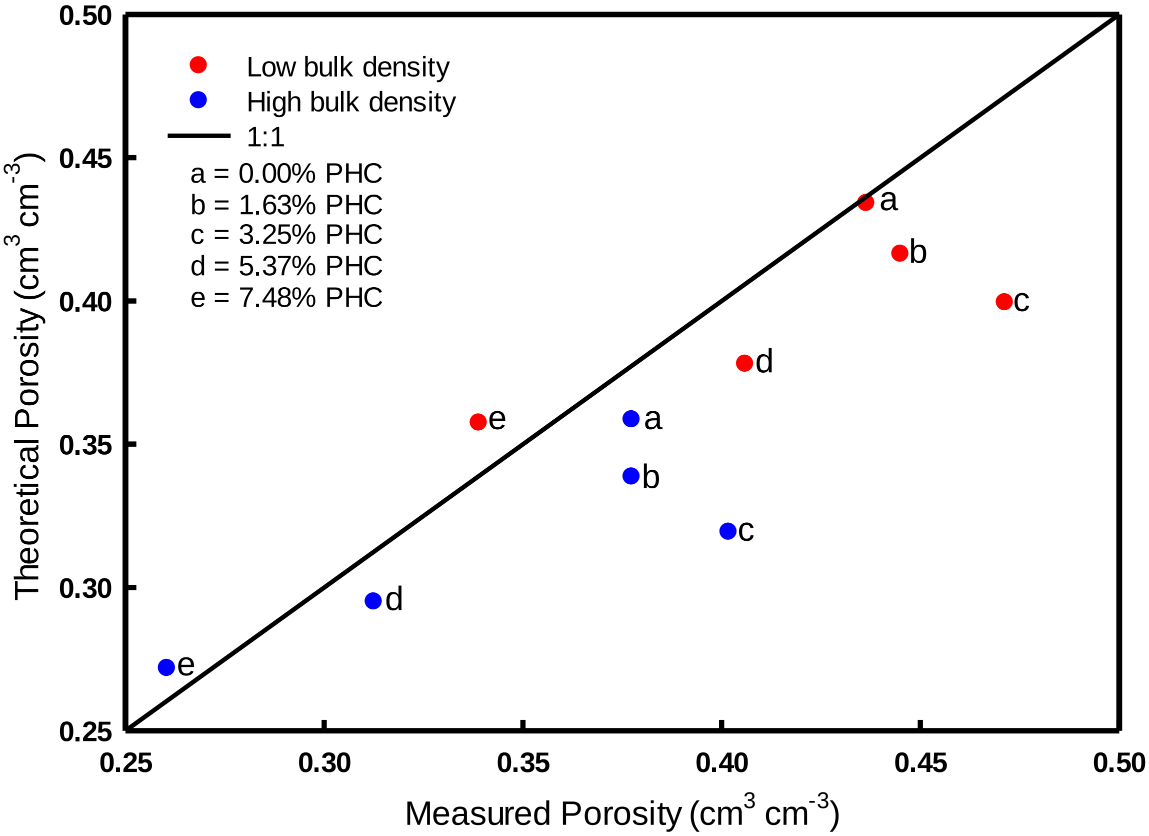


**Figure 3.5.** Relationship between the theoretical (calculated) porosity with volume of PHCs taken into account, and the measured porosity (saturated water content ($\theta_s$)).

Figure 3.3(d) shows how PHC concentration and bulk density affects the field capacity ($\theta_{fc}$) of LOS. The effect that PHC concentration has on the $\theta_{fc}$ is similar to that of the $\theta_s$, with some minor changes. The water retention at field capacity in the low bulk density samples is the same in the 0% and 1.63% PHC samples as well as in the 1.63% and 3.25% PHC samples. The $\theta_{fc}$ in the 3.25% sample is significantly higher than the 0% PHC sample, but then the $\theta_{fc}$ significantly drops in the 5.37% and 7.48% PHC samples. The effect of bulk density on $\theta_{fc}$ is opposite to what it was for $\theta_s$. Rather than the low bulk density LOS retaining more water at field capacity, the high bulk density LOS has higher water retention under these conditions. This results from the higher bulk density LOS having more micropores than the low bulk density LOS (Table 3.3), leading to higher soil water content at the suctions corresponding with field capacity.

The volumetric water content at permanent wilting point ($\theta_r$), shown in Figure 3.3(e), is significantly higher in the high bulk density LOS (Table 3.3). This is the result of higher microporosity in the high bulk density LOS (Table 3.3). There is no significant difference in the $\theta_r$ between the 0% and 1.63% samples at both bulk densities, but in the high bulk density samples, $\theta_r$ significantly decreases in each of the three increasing PHC concentrations. The significant reduction in $\theta_r$ is likely caused by PHCs filling in the micropore space of those samples as Table 3.2 shows, there is a significantly lower microporosity in the higher PHC concentration LOS samples.

Typically, the added presence of organic carbon in the form of soil organic matter (humus, peat, etc.) increases porosity and water retention in the soil, especially in a coarse textured soil with low organic carbon content (Rawls et al., 2003) such as LOS. However, PHCs differ from typical soil organic matter in their composition and impact on the soil physical characteristics as Mossop (1980) explains, the Athabasca oil sands deposits are unique in the sense that the oil is located in the interior of the pore space rather than coating the individual soil particles. As PHC concentration increases, more of the soil pore space is filled with hydrocarbons leaving less pore space for water to occupy. Technically, the soil porosity is not being reduced, however, Mossop (1980) explains that the PHCs in the LOS are immobile. This causes them to act as more of a solid phase in which they sit in the pores and block the pore space available for water to occupy and flow through. In this sense, one may think of PHCs reducing the soil pore space. PHC concentration was found to have little effect on the macroporosity in LOS (Table 3.3). It was also found that an increase of PHC concentration in LOS was associated with a decrease in the PWP. This could be a result of PHC related repellency which Tillman et al. (1989) explains, is associated with organic coatings on the soil particles. Letey et al. (1962) showed that infiltration of ethanol into soil is unaffected by repellency. Therefore, to test if the reduction of the water content at PWP was a result of incomplete saturation due to repellency, separate cores of LOS packed to 1.5 g $cm^{-3}$ bulk density and 7.48% PHC were saturated with ethanol and water. It was found that hydrophobicity did not play a role in significantly reducing saturation as the volume of ethanol and water was the same in their respective saturated cores. Considering this, since the PHCs most likely fill the pores of the soil rather than coating the individual soil particles (Mossop, 1980), it is likely that the PHCs preferentially fill the smaller pore volumes (micro- and mesopores) over the larger pore volumes.

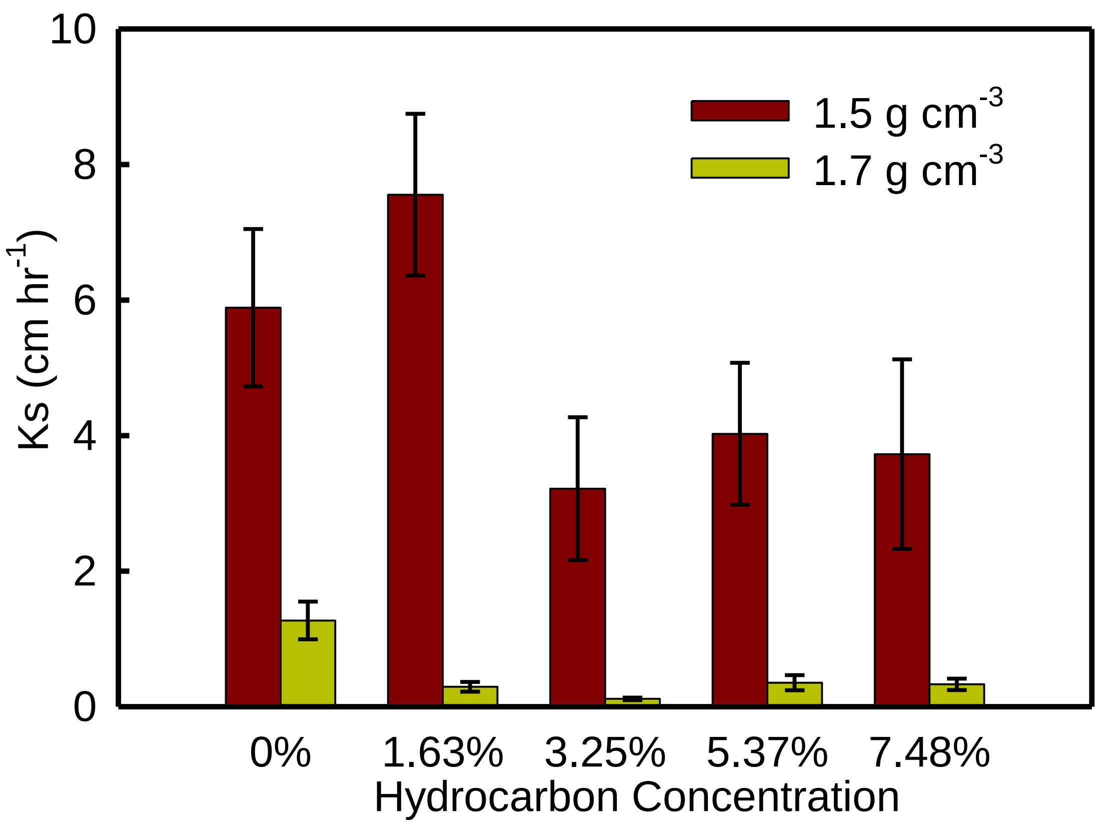


**Figure 3.6.** Saturated hydraulic conductivity of LOS at various PHC concentrations and bulk densities.

The results of saturated hydraulic conductivity ($K_s$) of each LOS sample can be seen in Figure 3.6. High bulk density significantly reduced the $K_s$ of LOS. Table 3.3 shows that a 0.2 g $cm^{-3}$ lower bulk density results in a nearly one order of magnitude increase in $K_s$. An increase in PHC concentration resulted in a decrease in $K_s$ for both bulk density samples. For the lower bulk density LOS, treatments of 0 and 1.63% had significantly greater $K_s$ than the higher PHC treatments; and the higher bulk density LOS with 0% PHC had a higher $K_s$ relative to the PHC treatments of 1.63% and greater. The 3.25% PHC treatment with a high bulk density had significantly lower $K_s$ than all other treatments, likely due to the increased clay content (Table 3.1). The $K_s$ reducing effect of PHC concentration is not as pronounced as the effect of bulk density, because the PHCs are likely filling the smaller non-water conducting pores which are not as critical to soil water flow. It is possible however, especially in the high bulk density LOS, that the lower mesoporosity (Table 3.2), due to the PHCs filling the pores, reduces the connecting porosity that is required for macropores to conduct water. With the connections of the main pathways for water flow cut off, the water will not be able to flow through the soil, effectively reducing the $K_s$ of the LOS. Mitchell and Soga (2005) explain that the $K_s$ of a soil is related to the soil's void ratio ($e$), (from here-on out, referred to as $e$ effective ($e_{eff}$)), or the ratio of open pore space to soil solids. According to Mitchell and Soga (2005), $K_s$ varies with:

$$e_{eff}^3/(1+e_0) \tag{3.4}$$

where $e_0$ is a reference void ratio ($e$ at 0.0% PHC and 1.5 g cm$^{-3}$ bulk density) and $e_{eff}$ is the effective void ratio for a saturated, coarse textured soil. In order to calculate $e_{eff}$ in equation 3.4, you must first calculate $e$:

(3.5)

$$e = \frac{\rho_p}{\rho_b} - 1$$

where $e$ is the soil's void ratio, $\rho_p$ is the particle density (2.65 g cm$^{-3}$) and $\rho_b$ is the bulk density of the soil (g cm$^{-3}$). Since the PHCs are filling the pores of the soil, they are reducing the soil porosity which affects the void ratio. As PHCs increase, the void ratio ($e$) decreases, resulting in a reduction of open pore space available for water to flow through. To take this into account, the volume of PHCs (calculated by dividing the mass of PHC (g) by the bulk density (g cm$^{-}$3) of the LOS) in the soil is subtracted from Mitchell and Soga's (2005) void ratio ($e$) resulting in the effective void ratio ($e_{eff}$) which is used in equation 3.4. Figure 3.7 shows the comparison of the saturated hydraulic conductivity with the effective void ratio and void ratio of the LOS.

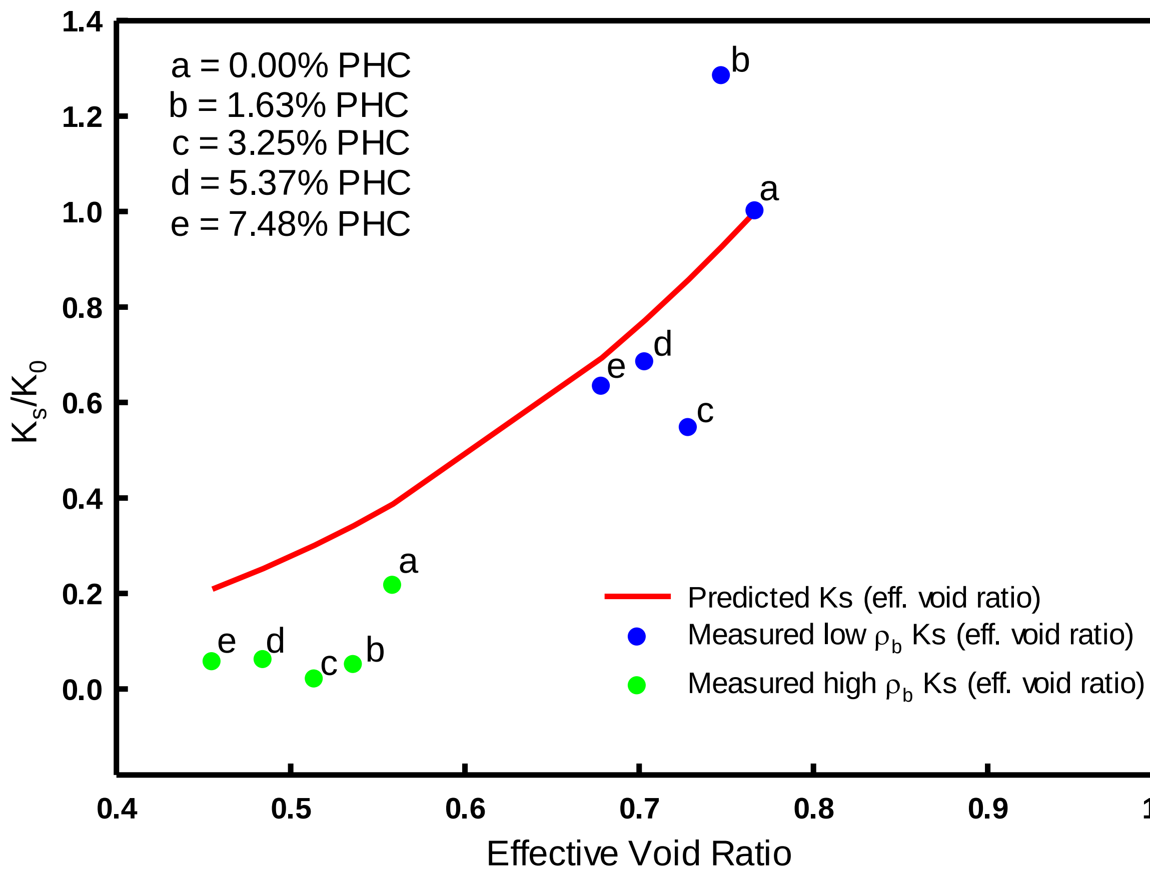


**Figure 3.7.** $K_s/K_0$ graphed as a function of the void ratio of LOS, where $K_0$ is the reference saturated hydraulic conductivity (the low bulk density (1.5 g $cm^{-3}$) and 0.0% PHC concentration LOS treatment), and $K_s$ is the saturated hydraulic conductivity of each LOS treatment.

Figure 3.7 compares the predicted $K_s/K_0$, calculated by using the values generated from equation 3.4 for each of the LOS treatments. The predicted $K_0$ value was set at 1 by dividing the predicted value for the low bulk density and 0.0% PHC concentration by itself. The values for $K_s/K_0$ were then calculated for each subsequent LOS treatment and plotted against their effective void ratio ($e_{eff}$). These were then compared to the measured $K_s/K_0$ values in Figure 3.7. The predicted $K_s/K_0$ was also plotted against the void ratio (e) which is on the top x-axis and is represented by the triangles. The line represents the trend in predicted values, and the circles represent the measured values. The line for the predicted values has an upward trend. Both the measured high bulk density and low bulk density LOS samples also trend upward as PHC concentration decreases due to the increasing $K_s$ in lower PHC samples therefore, effective void ratio (equation 3.4) reflected the trend. However, the measured values had a consistently lower $K_s/K_0$ than the predicted values. It was mentioned earlier that even though the PHCs are not filling the larger pores which conduct water through the soil, they may be filling the smaller pores of the soil that act as connecting pores to the main water conducting pores. This reduces $K_s$ as PHCs increase and is evident in Figure 3.7. In addition to the PHCs, the increased clay content of the 3.25% PHC samples of LOS resulted in clay particles further blocking the connecting porosity and lead to the lowest $K_s/K_0$ in their respective bulk densities.

The differences in bulk density and PHC concentration influenced the hydraulic properties of LOS mainly by affecting the soil's porosity. Throughout the above results, it was discussed how the PHCs fill the pores of LOS and evidence suggests that they may be preferentially filling the micropores more than they fill the meso- and macropores. Therefore, rather than acting like typical organic carbon does where it will improve the structure of the soil, increasing the porosity (Rawls et al., 2003), they decrease the porosity by filling the pore space. This will likely affect the soil water in the overlying reclamation cover as well as the response of environmental receptors such as vegetation. The increase in PHC concentration reduces overall water retention of LOS which may be a problem for plants needing to access the water in the LOS layer. On the contrary, AWHC in LOS increases as bulk density increases, and the reduced $K_s$ in higher PHC concentration LOS will limit the downward movement of water through the

LOS, resulting in higher water storage in the overlying reclamation soils. This will increase the water storage in the root zone resulting in the increased access of water and nutrients for plants, and for a longer period of time. The reduced $K_s$ of LOS at higher bulk densities will also limit the downward flow of water and with it, contaminants through the base LOS layer to groundwater. In light of this evidence, it may be possible to adjust the placement of LOS in the profile (higher or lower) to optimize the water content required for recreating more specific water regimes and ecosites using the available, coarse textured, reclamation soils.

### 3.5 Conclusion

This study demonstrates that both bulk density and PHC concentration influence the hydraulic properties of LOS. The effect of PHCs on soil hydraulic parameters was previously unknown. It was found that PHCs do not act the same as typical soil organic matter. Rather than increasing porosity by improving soil structure, PHCs reduce soil porosity by filling the pores of the soil. This results in a reduction of soil water retention of LOS as PHC concentration increases. The AWHC of LOS however, was more affected by the texture and bulk density than it was by PHC concentration. This is likely due to PHCs mainly filling the micropores of the soil rather than the meso- and macropores. In addition, the PHCs in LOS were found to have significant effects on the values of the $\alpha$ and $n$ parameters, which are reflective of the shape of the water retention curve. The differences in these parameter values however, held little physical meaning as the shape of the water retention curves experienced minimal change. At higher concentrations of PHC, the LOS exhibited lower $K_s$, likely due to the reduction in connecting pores, as macroporosity was unaffected by PHC concentration. This effect is also supported by the comparison of the relationship between the predicted and measured $K_s$ with the soil void ratio. The predicted $K_s$ was consistently higher than the measured $K_s$, while exhibiting the same trend. This is a possible representation of the effect of PHCs not only reducing the void ratio, but filling the connecting pores, further reducing the $K_s$ below what the predicted values were. Furthermore, the reduction in $K_s$ occurred at a lower PHC concentration (1.63%) in the high bulk density LOS due to the greater influence of PHCs in a lower porosity soil, shown by the reduction in the mesoporosity in higher bulk density LOS. When the porosity of the soil was higher (at lower bulk density), the effect from PHCs only became evident at a PHC concentration of 3.25%. It is possible that, as the concentration of PHC in the LOS becomes high enough (around 3.25%), it reaches a threshold where the water storage reducing effects that PHCs have on the LOS becomes significant.

The results of this study improve our understanding as to how PHC concentration affects the hydraulic properties of LOS. The results suggest that the placement of LOS as the base layer in reclamation will increase the soil water storage in the overlying reclamation profile and impede the downward flow of contaminants to the groundwater. This will lead into further studies on how the use of LOS in a reclamation cover will influence the hydraulic dynamics in the overlying soil profile. This knowledge will also help guide the placement of LOS in reclamation soil covers to increase the probability of creating a self-sustaining ecosystem required for the successful reclamation of disturbed land.

# 4.0 Effects Of Lean Oil Sand Overburden On The Water Dynamics In The Overlying Reclamation Cover

## 4.1 Preface

In Chapter 3, it was shown that both PHCs and bulk density affect the hydraulic properties of LOS. Increasing PHCs reduced the water retention and the saturated hydraulic conductivity of LOS. An increase in bulk density also reduces the saturated hydraulic conductivity and water retention at saturation, however increased bulk density increased the AWHC of LOS. What does this mean for water storage in the overlying profile and how does it affect the success of reclaiming the soil? In this chapter, LOS with varying PHC concentrations and bulk densities, are packed as the base soil layer in a soil column, replicating a reclamation prescription. The effects that LOS has on the water storage and nutrient retention capacity in the overlying profile are examined. The results of this study are important for the success of reclaiming coarse textured soils using LOS overburden as the base soil layer.

### 4.2 Introduction

Oil sands developments in Northern Alberta have resulted in large amounts of disturbed land in need of reclamation. The three main hydrocarbon rich oil sands deposits (Peace River, Cold Lake and Athabasca deposits) that compose the Alberta Oil Sands, are the second biggest oil reserve in the world and cover an area of 140,000 $km^2$ (GOA, 2009; Johnson and Miyanishi, 2008). Over the area that the oil sands underlie, it is approximated that over 4,800 $km^2$ of land will be affected (GOA, 1993). The company that holds the lease for the production of oil is required to return all of the disturbed land to pre-disturbance, equivalent capabilities based on the Environmental Protection and Enhancement Act of Alberta. The soils that are excavated in the process of mining the hydrocarbon rich oil sands include the LFH, peat, topsoil, subsoil and overburden material. Many of the excavated soils, which are stockpiled for the use in reclamation, are mostly coarse textured glaciofluvial and aeolian deposits (Zettl et al., 2011), which have a poor water holding capacity. This makes reclamation with these soils challenging, as there is low availability of water and nutrients for the growth and establishment of plants. Methods such as soil layering help to remedy this problem, as Zettl et al., (2011) found that layering of coarse textured soils increases the water content in the soil profile at field capacity. In some cases, there may be limited types of material available, or the ones that are available do not have high enough textural contrasts. For the latter case, layering those materials may not be effective in increasing soil water storage. Dobrovolskaya et al. (2014) showed that layering the fine over the coarse soil fractions obtained by fractionating medium sand, allowed increased soil water storage. Soil layering alone, however, may not be sufficient for creating the specific ecosites that would be required to return the land to equivalent capabilities.

The overburden material that is excavated in the oil sands mining process is called lean oil sand (LOS). LOS has a petroleum hydrocarbon (PHC) concentration of less than 8% (Visser, 2008), which makes it uneconomic for companies to extract. It is hypothesized that implementing LOS as the base soil layer, in which the subsoils and nutrient rich topsoils will overlie, may increase the water storage in the overlying profile and reduce the flow of water out of the root zone. This additional water storage in the profile above the LOS will increase the plant available water and nutrients, which will aid in the re-vegetation and establishment of the desired ecosites.

The objective of this research is to determine how the implementation of LOS as the base reclamation material will affect the water storage capacity and nutrient retention in the overlying soil profile. In addition, various bulk densities and PHC concentrations of LOS were tested to determine how the hydraulic dynamics of the reclamation profile respond to variations in these properties. Soil columns were packed with a soil layering prescription that is currently being used in oil sands reclamation, which includes a base layer of LOS. The columns enabled the measurement of water storage under different moisture conditions as well as the determination of nutrient breakthrough curves for the soil profiles. This research will help determine how varying bulk densities and PHC concentrations of the base LOS layer in oil sands reclamation will affect the plant available water and nutrients in the overlying soil profile.

**4.3 Materials and Methods**

North of Fort McMurray, Alberta is Syncrude Canada Ltd.'s Aurora North oil sands mine. Located at the Aurora North mine is a large oil sands reclamation study called the Aurora Soil Capping Study (ASCS). The ASCS is a 36 hectare, long-term, instrumented watershed research site that has been designed to study the reclamation of oil sands disturbed land. Various soil layering prescriptions, using the coarse textured soils that had been previously excavated in the mining process, are being tested at this site. One of the main components of the ASCS is the layer of LOS which underlies all other reclamation soils across the entire area of the ASCS. What was previously a LOS stockpile has now been compacted and graded to form the base of the ASCS, on top of which all other reclamation soils would be placed. This resulted in spatial variation of bulk density and PHC concentration in the base LOS layer across the ASCS. The variations in PHC and bulk density in the LOS will potentially cause differences in the hydraulic dynamics of the overlying soil profile. This would result in heterogeneity in water and nutrient storage in the soil across the ASCS and affect how planted vegetation establishes and grows. It is, therefore, important to understand the effects that PHC concentration and bulk density would have on the hydraulic dynamics of the soil profile.

Stockpiled reclamation soils were sampled from Syncrude's Aurora North Mine. The samples that were collected from stockpiles naturally occur in the area and were excavated during the process of mining the oil sands. These soil samples were collected in accordance with one of the soil layering prescriptions that is being tested at the ASCS and included peat, a blended B/C horizon (subsoil) sand and LOS, which was taken directly from the ASCS. Multiple samples of LOS were taken from two different areas of the ASCS with the intention of gathering LOS with varying PHC concentrations. The two areas that LOS was taken from on the ASCS had previously been tested by Syncrude for PHC concentration. One sample area had an average PHC concentration of 2-4% by weight, and the other sample area had an average PHC concentration of 5-7% by weight. The LOS was removed using shovels, and placed into pails to be shipped to the University of Saskatchewan.

The two LOS samples were placed onto tarps and air dried. The samples of LOS, from their respective areas, were thoroughly mixed together to create two homogenous soils, one with a low PHC concentration and one with a high PHC concentration. The two LOS soils were then subsampled and tested for organic carbon content using the LECO C632 dry combustion carbonator (LECO Corp., St. Joseph, MI, USA) (Wang and Anderson, 1998). Due to the limited presence or absence of organic matter inputs in the LOS, it is assumed that any organic carbon detected was a result of the PHCs in the soil. In addition, particle size analysis (PSA) was conducted on the LOS samples using a Horiba LA-950 particle size analyzer (Horiba Scientific, Edison, NJ, USA).

Plexiglas columns with a height of 150 cm and diameter of 20 cm were used to pack and encase the soil. A 10 cm high plastic cylinder with the same diameter of the columns was fastened to the top of each column using silicone. This extended the columns allowing for extra head space for water application. Five columns were used in this experiment, resulting in the comparison of five different treatments. The layering prescription that was used in the columns consisted of a 25 cm top layer of peat followed by a 70 cm subsoil layer of the blended B/C horizon material. The subsoil sand material was underlain by a 40 cm layer of the LOS overburden followed by a 15 cm layer of filter sand to reduce the amount of fine particulates that flowed from the bottom of the columns with the effluent. One column was used as a control to determine what would happen in a reclamation cover with no LOS base layer and therefore, the bottom layer of LOS was replaced with the subsoil sand. In the other four columns, all materials were packed to the same conditions with the exception of the LOS, which varied in hydrocarbon content and bulk density. The subsoil sand layer in each of the columns was packed to a bulk density of 1.5 g $cm^{-3}$. Two columns had the LOS packed at the low bulk density of 1.5 g/cm$^3$, with one containing LOS at a PHC concentration of 3.25% and the other at a PHC concentration of 7.48%. The other two columns were packed in the same way, but at the high bulk density of 1.7 g/cm$^3$. The bulk density of the subsoil sand layer of each column was intended to be packed at 1.5 g/cm$^3$, however, the bulk densities varied between columns from 1.49 to 1.54 g/cm$^3$. Figure B2 shows the column setup.

When packing columns, it is critical for the packing to be as homogeneous as possible to prevent preferential flow, produce a smooth infiltration front (Oliviera et al., 1996), and reduce the influence of soil packing on the flow of solute through the columns (Bromly et al., 2007). The packing methods used in these columns were intended to reduce micro-layering within each layer of soil. Since the columns were 150 cm tall, dropping dry soil into the columns caused coarse particles to settle first, and finer particles to become suspended in the air and settle in thin layers on top of the coarser soil, creating micro-layers of dominantly silt and clay particles; thus reducing homogeneity. To remedy this, soil was packed at a moisture content of 5% water content by weight, eliminating the separation into fine and coarse particles that would occur when dropping dry soil into the column. The 5% moisture content was selected based on the findings of Panayiotopoulos (1989), which states that the soil void ratio is stable at that moisture content. The top of each lift was also scarified before a new lift was added, which reduced micro-layering and segregation by particle size (Plummer et al., 2004). Oliviera et al. (1996) found that smaller lifts of 0.2 cm have been shown to create the most homogeneity in packing columns, however, Plummer et al. (2004) found that packing in lifts of up to 15 cm thick have also been shown to pack uniformly. In trial runs of packing the columns, lifts of 5 cm and greater were seen to create micro-layering thus, the columns were packed in lifts of approximately 0.5 cm to 1 cm, which was sufficient in reducing the occurrence of any micro-layering.

Prior to packing the LOS in the column, a semi-permeable nylon membrane with an air entry value of $\Psi$ = 30 kPa, was placed at the boundary between the filter sand and the LOS. The membrane allows the passage of water but prevents the passage of air at suctions less than 300 cm. The membrane was fixed in place by using silicone to seal the edges of the membrane against the inside wall of the column. A funnel was placed inside the bottom of the column to direct the effluent to a hole in the center of a cap which was glued to the bottom of the column. Through the hole in the center of the bottom cap, a valve was installed to allow the water to drain from the bottom of the column. Attached to the valve was a hose (where the effluent would drain out), which was placed into a hole in the side of a 5 gallon pail where the effluent was contained. The hole in the pail was set at 10 cm below the nylon membrane, effectively creating a lower boundary condition of 10 cm of suction at the bottom of the LOS layer. This allowed for the replication of capillary forces under unsaturated conditions, as at the ASCS, this layer in the profile would be part of the vadose zone. Each column had time domain reflectometry (TDR) rods installed to monitor the volumetric water content. Ten sets of TDR rods were placed in each column, one directly above and below each layer boundary, including the bottom of the LOS layer, and at 10 cm intervals throughout the subsoil sand layer (Fig. B2).

The column experiment was designed to test how changes in bulk density and PHC concentration of the base LOS layer would affect the water storage and nutrient retention in the overlying reclamation profile. It should be noted that this study only ran one set of columns with no replicates and was intended to confirm expected results based on the knowledge gained from the experiments in chapter 3. The columns were tested in 3 phases; the first phase was to test the water storage at saturation and at field capacity (static water storage). To saturate the columns, water was applied to the top of each column. A pressure head of 10 cm of water was maintained until water was continuously pouring into the collection pails and 38 litres of water was poured onto each of the columns. The TDR cables were attached to multiplexers, which relayed the TDR signals to a TDR 100 (Campbell Scientific Inc., Logan, Utah, USA). The TDR 100 calculated the volumetric water content and sent that to a CR-10X data logger (Campbell Scientific Inc., Logan, Utah, USA) to be stored and downloaded to a computer. Once the columns were saturated, they were allowed to drain to field capacity for 72 hours, as Veihmeyer and Hendrickson (1950) suggest that field capacity is achieved after the drainage of excess water for 2 to 3 days following rain or irrigation. During this drainage time and for the duration of the column experiment, when water was not being actively applied, caps were placed on the top of each column to eliminate any water loss that would occur due to evaporation.

The second phase of the study was to observe how the water storage in the columns would react to an additional pressure that would reduce the water content below field capacity (dynamic water storage). A pressure of 30 kPa was applied to the top of each column, and was intended to push water out of the profile, replicating the loss of water from the profile due to plant root uptake. The pressure was applied for six days, followed by a "worst case scenario" extreme rainfall event of 94.5 mm that was recorded in Fort McMurray in 1976 (El Dorado Weather, 2014). Immediately after the water was applied to the top of the column, the pressure was re-applied and this process was carried out two more times.

The purpose of the third phase of the study was to determine the nutrient retention of each profile. A potassium chloride tracer was applied in a spike input to the top of each column, immediately followed by the same "worst case scenario" rainfall event that was applied in phase two. This rainfall event was applied to each column once every 24 hours for six days. An electrical conductivity (EC) meter was used to measure the EC of the effluent every 4 hours. The nutrient breakthrough curves were then plotted as EC over time and give an idea of how the nutrient retention for each column responds to the variability in rainfall events over time rather than a continuous flow of water leaching through the soil, and are not corrected for the volume of effluent tested. Since the water flow out of the soil columns was transient, it may be more beneficial to plot the EC as a function of cumulative infiltration. Therefore, the curves were also plotted as the probability density function (PDF) over cumulative outflow. The probability density function (PDF) (1/s) is the ratio of solute flux at the bottom of the column at time step (i) to the total amount that was added per unit area (MPA), and can be calculated by:

$$PDF_i = \frac{Js_i}{MPA} \tag{4.1}$$

MPA is the mass per unit area, calculated as:

$$MPA = \sum_{1}^{n} (Js_i \times \Delta t_i) \tag{4.2}$$

Therefore:

$$PDF_i = \frac{Js_{\mathrm{i}}}{\sum_1^n (Js_i \times \Delta t_i)} \tag{4.3}$$

where subscript i represents the time step, n is the total number of time steps, $\mathrm{t} = \sum_1^{\mathrm{n}} \Delta \mathrm{t_i}$, $Js_i$ is the flux of solute ($cm^3\ cm^{-2}\ s^{-1}$) at time step i, and $\Delta t_i$ is the time increment from time step i to i+1. Because the solute flux is equal to the product of water flux and solute concentration, Eq. (4.3) can be rewritten as:

$$PDF_i = \frac{Jw_i \times C_i}{\sum_1^n (Jw_i \times C_i \times \Delta t_i)} \tag{4.4}$$

Where $C_i$ is concentration at time (t) for time step i and can be written as EC:

$$C_i = \alpha EC_i + \beta \tag{4.5}$$

$$C_0 = \alpha EC_0 + \beta \tag{4.6}$$

where $EC_i$ is the electrical conductivity measured at time step i, and $EC_0$ is the background electrical conductivity before application of solute to the soil column. α and β are the regression line slope and intercept between the measured concentration C and the electrical conductivity. The response of solute concentration in effluent to the applied solute can be written as:

$$C_i - C_0 = \alpha EC_i - \alpha EC_0 \tag{4.7}$$

$$= \alpha(EC_i - EC_0) \tag{4.8}$$

Therefore:

$$PDF_i = \frac{Jw_{\mathrm{i}} \times (EC_{\mathrm{i}} - EC_0)}{\sum_1^n (Jw_i \times (EC_i - EC_0) \times \Delta t_i)} \tag{4.9}$$

Where t is time (s), $Jw_i$ is the flux of water ($cm^3\ cm^{-2}\ s^{-1}$) calculated from the difference between Jw at the previous time step (i-1) and Jw at the following time step (i+1) relative to time (t), resulting in Jw at time step i:

$$Jw_i = \frac{(Q_{i+1} - Q_{i-1})}{2\Delta t_i} \tag{4.10}$$

where Q is the cumulative flow rate ($cm\ s^{-1}$).

Normally, we would plot the PDF as a function of time, because the probability density function as a function of time can be used to calculate the mean travel time, and the product of

PDF at a time with MPA gives the breakthrough concentration at that time. However, Eq. 4.9 requires the flow to be steady state. Since the flow in our experiment is transient, following Jury (1990), the breakthrough curves are expressed as concentration C as a function of cumulative outflow Q. Then the probability density function ($PDF_Q$) (1/cm) is defined as the ratio of solute mass contained per unit Q increment ( $\Delta$ Q) at the bottom of the column to the total solute mass that was added, and can be calculated by:

$$\mathrm{PDF_Q(Q_i)} = \frac{(\mathrm{C_i} - \mathrm{C_0}) \times \mathrm{A} \times \Delta\mathrm{Q_i}/\Delta\mathrm{Q_i}}{\sum_1^n\big((\mathrm{C_i} - \mathrm{C_0}) \times \mathrm{A} \times \Delta\mathrm{Q_i}\big)} = \frac{(\mathrm{C_i} - \mathrm{C_0})}{\sum_1^n\big((\mathrm{C_i} - \mathrm{C_0}) \times \Delta\mathrm{Q_i}\big)} \tag{4.11}$$

where A is the area ($cm^2$). Since $C_i = \alpha(EC_i\text{-}EC_0)$, Eq. (4.11) becomes:

$$PDF_Q(Q_i) = \frac{EC_i - EC_0}{\sum_1^n((EC_i - EC_0) \times \Delta Q_i)} \tag{4.12}$$

By definition, the area under the curve $PDF_Q$ (1/cm) as a function of cumulative outflow (cm) is equal to one.

## 4.4 Results

Table 4.1 displays the PSA of the LOS samples used in this experiment. The high PHC concentration LOS had a loamy sand texture due to its relatively high sand content and low clay content, whereas the elevated clay and silt content of the low PHC LOS, resulted in a sandy loam texture.

**Table 4.1.** Particle size analysis of LOS samples using the HORIBA LA-950 Particle Size Analyzer

| | Soil Separate (%) | | | Texture |
|---|---|---|---|---|
| PHC (%) | Sand | Silt | Clay | Class |
| 3.25 | 54.95 | 33.90 | 11.15 | Sandy Loam |
| 7.48 | 73.85 | 25.98 | 0.17 | Loamy Sand |

The cumulative water storage in the subsoil sand and peat layers, under various hydraulic conditions, were measured in each column (Fig. 4.1). It should be noted that, due to the placement of the TDR rod in the bottom of the peat layer and the need to calculate the average water storage in the entire peat layer, more water may have accumulated around the TDR rods than what was representative as average throughout the peat. This may have led to the calculated water storages for each column being slightly overestimated. At saturation, the water storage in the subsoil sand and peat layers (which directly overlie the LOS) is very similar among all columns. When draining from saturation to field capacity, a large drop in water storage was observed, but Column 2 lost less and stored more water than the other columns. Since the LOS in Column 2 is packed at the high bulk density (1.7 g $cm^{-3}$) and the high PHC concentration (7.48%), the LOS did not permit the passage of water through to the collection pail.

Figure 4.2 shows water drainage curves, which display the response of water content in each column, from just before saturation to field capacity, in the top (Fig. 4.2 a), middle (Fig. 4.2 b), and bottom (Fig. 4.2 c) of the subsoil sand layer, which directly overlies the LOS. In Figure 4.2, the water content in the middle (Fig. 4.2 b) and bottom (Fig. 4.2 c) of the subsoil sand layer in Column 2 is seen to increase with saturation and then flat lines and does not drain like the other columns do. Columns 3 (low bulk density, high PHC concentration) and 4 (high bulk density, low PHC concentration) had the next highest water storages (Fig. 4.1) followed by Column 5 (low bulk density, low PHC concentration) and the control with no base LOS layer showing similar water storage.

The dynamic water storage is the water storage in the profile once the pressure had been applied to the top of the column to replicate root water uptake. The water storages once again dropped from field capacity, but held the general trend between columns. It should be noted that since the LOS in Column 2 did not permit water to flow through to the collection pail, the water instead seeped out of the instrumentation ports in the side of the column. Vacuum grease was used in an attempt to block the flow of water through these gaps, however no amount of vacuum grease would stop the flow of water, likely resulting in a lower water storage in Column 2 than what it should be if the water had not seeped out of the side of the column. This effect would have been exaggerated under the dynamic conditions of added pressure as it further pushed water out of the gaps in the instrumentation ports.

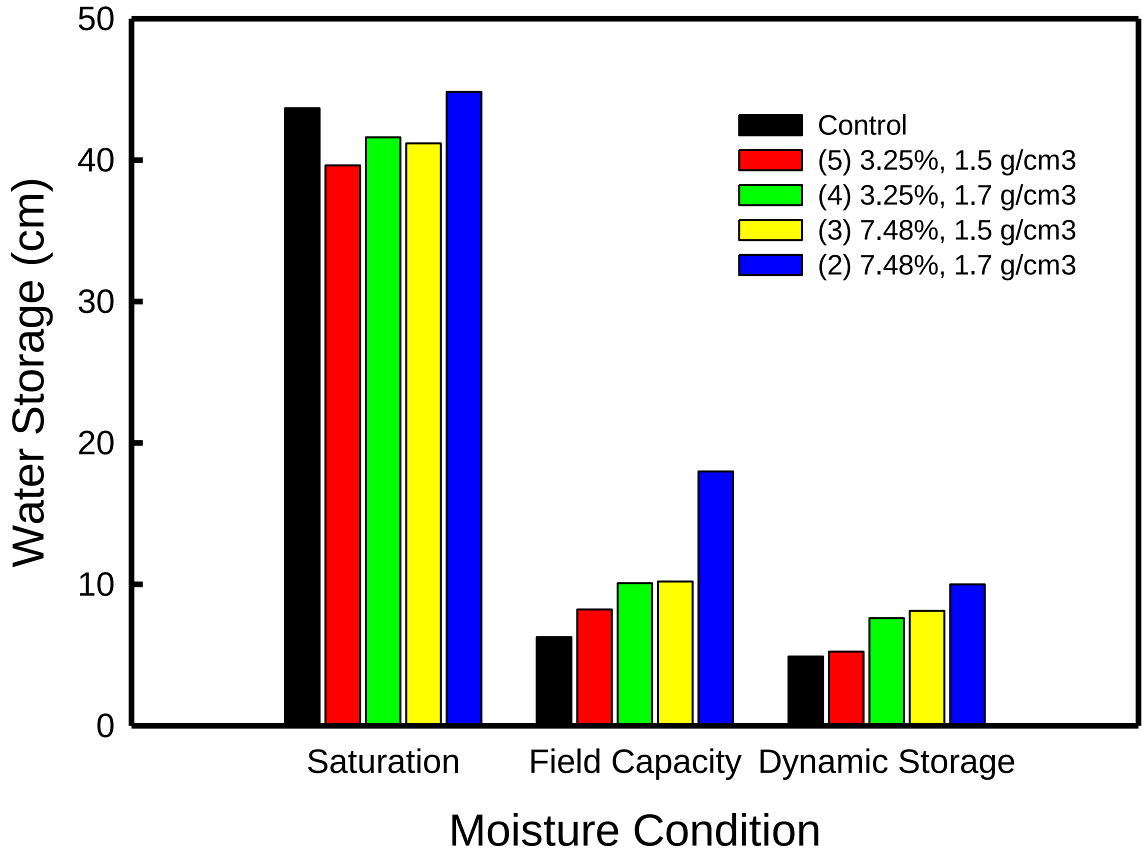


**Figure 4.1.** Water storage at various moisture conditions in the reclamation profile above the base LOS layer.

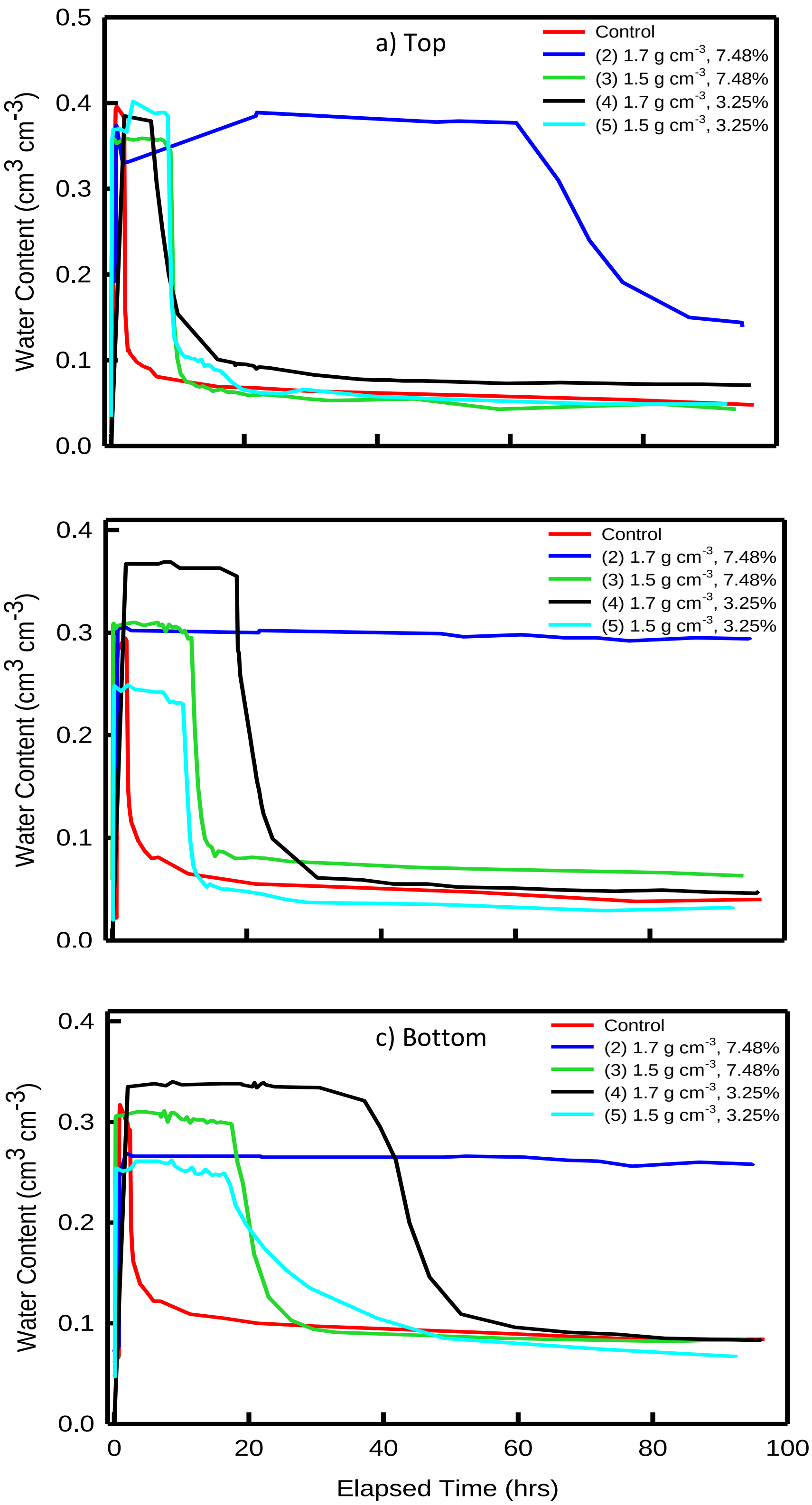


**Figure 4.2.** Water drainage curves measuring the change in water content from saturation to field capacity over time, in the top (a), middle (b), and bottom (c) of the subsoil sand layer which directly overlies LOS.

The nutrient breakthrough curves of each column, plotted as a function of EC over time are shown in Figure 4.3. These curves represent the measured EC in the effluent remaining in the collection pails at every four hour time increment (emptied after each reading) under conditions of worst case scenario rainfall events (94.5 mm). Rainfall events were applied every 24 hours over a 132 hour time period. Each curve in Figure 4.4 represents how effectively the columns retained the chloride tracer, in relation to the volume of water that passed through each column. Column 2 was not included in the results from the nutrient breakthrough curves. This is due to the lack of effluent to be tested, as the high bulk density and PHC concentration of the LOS in Column 2 did not allow for water to flow through, thus retaining the most water and nutrients in the profile out of all the columns.

In the nutrient breakthrough curves displayed in Figures 4.3 and 4.4, there are two groups of curves which are grouped by their peak times (Fig. 4.3) or peak cumulative outflows (Fig. 4.4). In the first grouping, the control column with no LOS, and Column 5 with the LOS packed at the low bulk density and low PHC concentration had similar peaks in their respective nutrient breakthrough curves (Fig. 4.3). However, the nutrient breakthrough curve for Column 5 showed a slightly higher EC at both earlier and later times (Fig. 4.3) as well as cumulative outflows (Fig. 4.4) and did not peak as high. The mean breakthrough water equivalent (BWE) was also calculated for each column. The BWE is the amount of precipitation that will be required to push the chloride tracer or nutrients through the profile. The mean BWE values for the columns had the same grouping trend as the peaks in the nutrient breakthrough curves. The control column had a mean BWE of 28.1 cm, and Column 5 had a mean BWE of 29.4 cm, however evapotranspiration must also be considered. Since some of the soil water will either be taken up by plants or evaporate from the soil, not all of the water that enters the soil through precipitation will contribute to pushing nutrients through the profile. Therefore, the calculated values for BWE will be underestimated to the extent of the evapotranspiration that would occur throughout the growing season.

The second grouping of nutrient peak times can be seen in comparing the nutrient breakthrough curves for Column 3 (low bulk density, high PHC concentration LOS) and Column 4 (high bulk density, low PHC concentration LOS). The breakthrough curve for Column 4 in Figure 4.3 is lower and shifted so that the initial breakthrough is later than column 3. The same trend can be seen between these columns in Figure 4.4. The breakthrough curve for Column 4 is shifted so that the breakthrough both begins and tails off at higher cumulative outflows. Even though the breakthrough curve for Column 4 is shifted, the peaks of the breakthrough curves for Columns 3 and 4 in Figures 4.3 and 4.4 occur at close to the same time and cumulative outflow respectively. As were the peaks in the nutrient breakthrough curves, the mean BWE for Columns 3 (33.6 cm) and 4 (36.3 cm) were also similar.

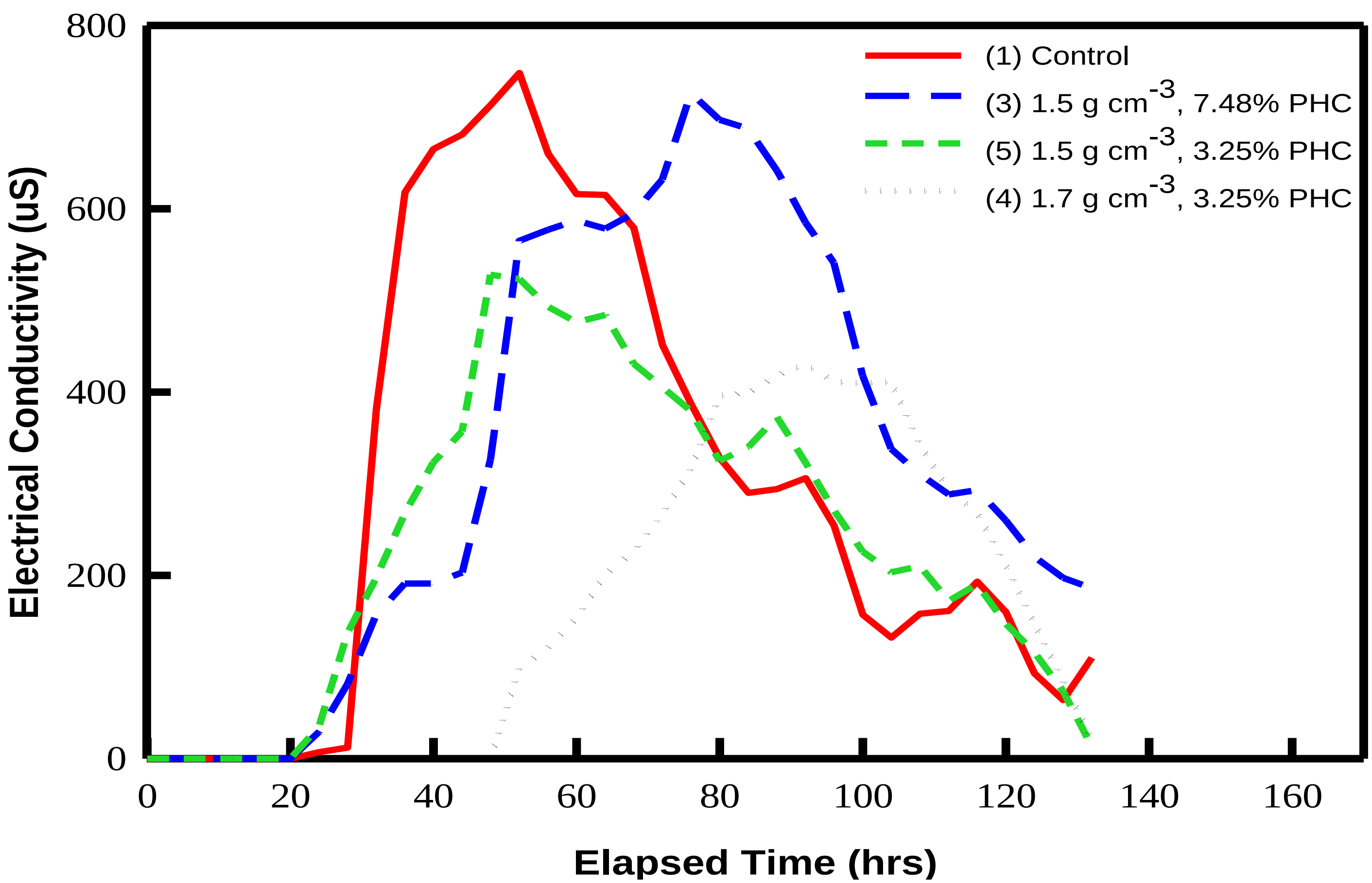


**Figure 4.3.** Nutrient retention curves plotted as a function of EC over time for columns packed with LOS as the base soil layer.

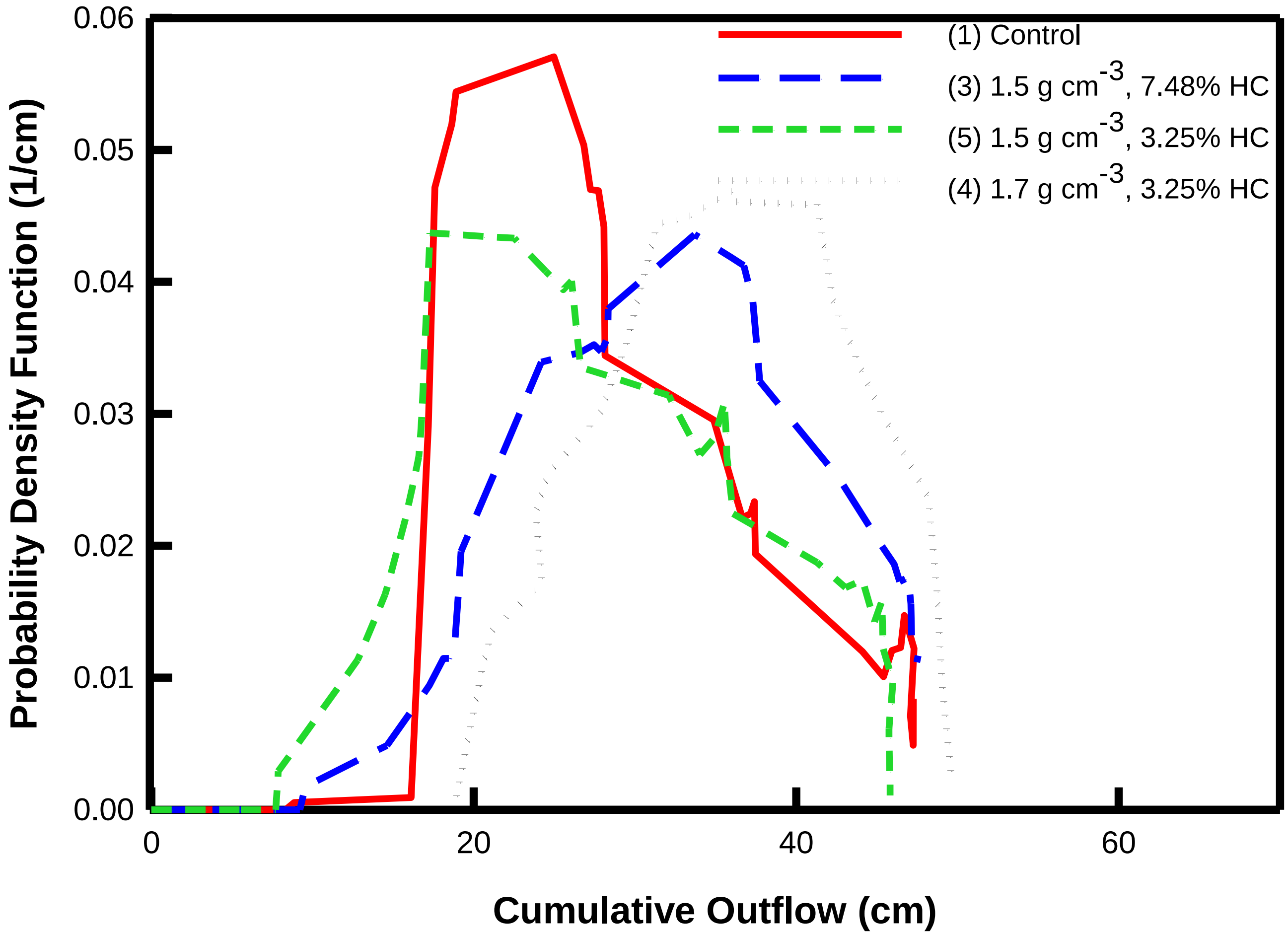


**Figure 4.4.** Nutrient retention curves plotted as a function of the probability density function over cumulative outflow for columns with LOS as the base soil layer.

### 4.5 Discussion

Figure 4.1 shows that a higher bulk density of LOS increases water storage in the overlying profile when comparing columns with similar PHC concentrations but different bulk densities (Column 3 (low $\rho_b$) and Column 2 (high $\rho_b$)) which had the high PHC concentration (7.48%), and Column 5 (low $\rho_b$) to Column 4 (high $\rho_b$), which both had the low PHC concentration (3.25%). In addition, when comparing columns with similar bulk densities but different PHC concentrations, (Column 3 to Column 5) and (Column 2 to Column 4), it is observed that higher PHC concentration in the LOS results in more water in the overlying reclamation profile. This can be attributed to the reduction in pore space from packing at the high bulk density as well as the higher PHC concentration. According to Mossop (1980), unlike typical soil organic matter, the PHCs in LOS reduce soil porosity as they reside in the interior of the pore space rather than coating the soil particles. This results in a decrease in pore space as PHC concentration increases. It has been observed that although PHCs reduce soil porosity, the macroporosity of the soil remains unaffected by PHC concentration (Chapter 3), so the reduction in saturated hydraulic conductivity (*Ks*) may be due to the PHCs blocking the connecting pores. With the connectivity between macropores (which conduct the flow of water through soil) blocked off, the water flow and nutrient transport through LOS is impeded (Chapter 3). This would explain the higher water storage in the overlying soil profile that is observed with higher PHC concentration in the LOS overburden, and is consistent with findings from Kelln et al. (2009) and Paragon Soil and Environmental Consulting Inc. (2006) which both observed in the field that the presence of a LOS layer or lens resulted in higher water content in the overlying soil. As PHCs fill pore spaces, the connecting porosity of the LOS decreases, reducing the flow of water through the soil, resulting in greater water retention as well as nutrient retention in the overlying profile.

When comparing the water storage in Column 4 (high bulk density, low PHC concentration) to Column 3 (low bulk density, high PHC concentration), it can be expected that Column 4 would have higher water storage in the overlying profile than that of Column 3 due to the higher bulk density and clay content of the LOS. However, Figure 4.1 shows that under both field capacity and dynamic water storage conditions, the water storages are very similar between Columns 3 and 4. The reduction of porosity by the presence of higher PHC concentration in the LOS of Column 3 (Chapter 3), was great enough to reduce the flow of water through that material and retain more water in the overlying profile, as though it contained the LOS with higher bulk density and clay concentration, similar to that of Column 4.

Since the primary transport of nutrients through soil is with the movement of water, the nutrient breakthrough curves should reflect the water storage (Fig. 4.1) and water drainage curves (Fig. 4.2) of the profile. Similar trends were seen between the nutrient breakthrough curves as were seen between the water storages in the columns. The control column and Column 5 had comparable water storages and nutrient breakthrough curves, and the same was observed for Columns 3 and 4. The water storage in the control column and Column 5 were the lowest (Fig. 4.1) and the nutrient breakthrough curves (Figs. 4.3 and 4.4) reflected this. Since the movement of water through these columns was more rapid, which can be seen in the water drainage curves in Figure 4.2, the water storages were lower. This rapid drainage also resulted in the movement of the chloride tracer through the column at quicker rates (Fig. 4.3) and lower cumulative outflows (Fig 4.4). This can all be attributed to the control column having no LOS layer to block water flow through the profile and Column 5 having the highest porosity LOS (low bulk density and low PHC concentration). These two columns also had the lowest mean BWEs (29.4 cm for the control, 28.1 cm for Column 5). According to Environment Canada (2015), the average annual precipitation for Fort McMurray is 41.9 cm. Since the BWE for the control column and Column 5 are approximately 30 cm each, and assuming no loss to evapotranspiration and with conditions similar to the columns, the nutrients in the profile would have the potential to be transported down through the profile in less than a year, based on the annual precipitation in Fort Mcmurray. Depending on the target ecosite being reclaimed, the water and nutrient retention for these columns may not be sufficient however, when reclaiming an ecosite which requires relatively dry conditions, the layering prescriptions in these columns may be sufficient.

An interesting trend that occurred in Column 5 in comparison to the control was the higher EC in the initial chloride breakthrough both in terms of time (Fig. 4.3) and cumulative outflow (Fig. 4.4), as well as in the later breakthrough. Due to the LOS layer in Column 5 holding more water at field capacity than the same volume of subsoil sand that replaced the LOS in the control column, the extra water in the LOS layer had more time to interact with ions in the LOS. Because of this, when the initial volume of water was added to the columns, the water sitting in the LOS was pushed out and it had a higher EC than the same volume of water that was sitting in the bottom of the control column. As for the later breakthrough, the LOS in Column 5 had a higher clay content than Columns 3 and 4 as well as the control. This resulted in a slower drainage at the bottom of the column (Fig. 4.2 c) as the column reached field capacity, leading to the increased nutrient breakthrough at the end of the curve in both Figures 4.3 and 4.4.

Columns 3 (low bulk density, high PHC concentration) and 4 (high bulk density, low PHC concentration), had very similar nutrient breakthrough curves, as they did similar water storages. Column 4 however, retained more water for a longer period of time at all profile positions (Fig. 4.2) than the other columns, except for Column 2 (high bulk density, high PHC concentration). Referring to the nutrient breakthrough curves in Figures 4.3 and 4.4, it would be reasonable to expect that Column 4 would have a later peak and more drawn out nutrient breakthrough curve than Column 3, because the higher bulk density and higher clay content (Table 4.1) of the LOS in Column 4 would restrict water flow. Similar to the trend in water storage between Columns 3 and 4, even though there is more breakthrough of chloride in Column 3 (mean BWE = 32.5 cm) at earlier times and lower cumulative outflows, the peak for the Column 3 breakthrough curve occurs at close to the same time and cumulative outflow as Column 4 (mean BWE = 36.3 cm). The earlier breakthrough of tracer in Column 3 corresponds with the water drainage curves in Figure 4.2 which shows an earlier spike in water content at saturation as well as quicker drainage throughout the profile than in Column 4. The elevated PHC concentration in the low bulk density LOS of Column 3 is slowing the flow of water and nutrients, shifting the nutrient breakthrough curve to a position more similar to that of a higher bulk density soil.

The trend of PHCs shifting the nutrient breakthrough curve is also observed when comparing the curve for Column 3 (low bulk density, high PHC concentration LOS) with Column 5 (low bulk density, low PHC concentration LOS). The only difference between these columns is the change in PHC concentration of the base LOS layer. Column 3 had the higher PHC concentration which lead to reduced porosity and a higher water storage in the profile overlying the LOS (Fig. 4.1) as well as nutrient breakthrough at a later time (Fig. 4.3) and higher cumulative outflow (Fig. 4.4). The same relationship exists between Column 2 and Column 4. Column 2 had the higher PHC concentration which led to the higher water storage in the profile.

Furthermore, due to the inability of the water to flow through the LOS, all of the chloride tracer remained in the overlying profile resulting in the absence of nutrient breakthrough for Column 2. From these trends it can be concluded that a higher PHC concentration leads to the reduced flow of water through the profile and an increased residence time of the chloride tracer solution, likely due to the decreased porosity in the LOS. This leads to the requirement of more precipitation and/or drainage time to push the chloride tracer through the soil profile. In addition to the aforementioned breakthrough curves which are plotted as EC over time, and the PDF plotted over cumulative outflow respectively, breakthrough curves were also plotted as PDF over pore volume and can be seen in Figure B3. In figure B3, the breakthrough of nutrients in each column peak at similar pore volumes (approximately 3.5 pore volumes), with exception of the column with low bulk density and low PHC concentration (2 pore volumes). In addition, each column has initial breakthrough of the chloride tracer at different pore volumes, starting with the low bulk density, low PHC column breaking through at the lowest pore volume, followed by the low bulk density high PHC column, then the high bulk density low PHC column, and finally the control column with no LOS. This may be misleading in interpretation however, due to each column varying in water storage at field capacity, which was used as the water storage for 1 pore volume. Since 1 pore volume represents different water storages in each column, the results the behaviour of the breakthrough curves in Figure B3, like in Figure 4.3, cannot be directly related to one another. However, these breakthrough curves give a sense of how many times over the water storage in the soil at field capacity is replaced before a contaminant would travel from the soil surface to the bottom of the profile.

Zettl et al. (2011) describes a variety of natural ecosite types that occur in the Alberta oil sands, each with different moisture regimes. These moisture regimes need to be replicated in the attempt to reclaim oil sands mining disturbed soils and re-establish pre-existing ecosites. Figure 4.1 shows that higher PHC concentration and bulk density LOS will lead to the most water storage in a profile at field capacity and at times of drought when the soil water is below field capacity. Figure 4.2 shows that when there is a surge of water as in the case of a rainfall event, the columns with high bulk density LOS kept more water in the overlying profile for a longer period of time than the low bulk density LOS. This may be ideal for reclaiming an aspen or spruce stand which requires relatively higher amounts of water to grow. However, when the desired vegetation is jack pine, the soil water requirements are much lower. The columns with the low bulk density LOS retained the surge of water for a shorter time than the high bulk density LOS columns however, the columns with the higher PHC concentration LOS, with similar bulk densities retained more water for a longer period of time (Fig. 4.2). With more water storage, there will also be more nutrient storage and the higher probability of successfully establishing new forest growth. Altering the combinations of PHC concentration and bulk density of the base LOS layer will aid in providing desired moisture regimes and the re-creation of specific ecosites. For example, Table A1 shows the CEMA (Cumulative Effects Monitoring Association) guidelines for determining moisture regimes, which lists the soil water requirements for specific ecosites. The control column, with no base LOS layer, had the lowest water storage at field capacity (63 mm) and Column 5 (low bulk density, low PHC concentration) had the next lowest water storage (82 mm). According to Table A1, these fall under the xeric or very dry moisture regime which is associated with an "a" ecosite and has coarse textured soil which drains rapidly. According to Beckingham et al. (1996), this type of ecosite supports mainly an open canopied jack pine stand with drought tolerant plants.  Columns 3 and 4 had field capacity water storage values of 102 mm and 101 mm, respectively. This water storage would fall under the subxeric moisture regime associated with a “b” ecosite with the potential to also be an “a” ecosite (Table A1). This moisture regime mainly contains coarse to moderately coarse textured soil which drains fairly rapidly (Table A1), and will support tree species such as pine, aspen, and white spruce (Beckingham et al., 1996). Finally, Column 2 which had the highest water and nutrient retention had a water storage at field capacity of 179 mm. This water storage is consistent with a subhygric or wet moisture regime and will support “e” or “g” ecosites (Table A1). The soil texture can be variable, depending on seepage, and drains very slowly. Beckingham et al. (1996) explains that these moisture regimes will support a diverse plant community including white spruce, black spruce, and balsam poplar. This goes to show that variations in bulk density and PHC concentration of the base LOS layer in reclamation of coarse textured soils can accommodate a wide range of moisture regimes which will support a variety of ecosites.

### 4.6 Conclusion

The bulk density and PHC concentration of the base LOS layer were both shown to have an influence on the nutrient retention and water storage in the overlying reclamation soil profile. An increase in bulk density of the base LOS layer was shown to increase the water storage in the overlying profile and retain water for a longer period of time, which in turn increases the nutrient residence time. In addition, as PHC concentration increased, the water storage and nutrient residence time in the overlying profile increased. It was observed that, despite a lower bulk density, increased PHC in the base LOS layer increased water and nutrient retention in the overlying profile similar to levels found in the column with a base LOS layer that had a higher bulk density and clay content, with less PHC. This leads to the conclusion that using LOS with higher PHC concentrations as the base layer in reclamation will increase water and nutrient retention. Furthermore, the placement of LOS with specific PHC concentrations and bulk densities as the base soil layer may result in the ability to achieve soil conditions that are specific enough to reclaim target ecosites. Nonetheless, due to the increased water and nutrient retention, using LOS as a base reclamation layer will aid in overcoming the challenges of successfully establishing new plant communities and reclaiming oil sands disturbed land, using the coarse textured soils in the Alberta oil sands.

# 5.0 SUMMARY AND CONCLUSION

The deforestation and excavation of land due to intense mining in the Alberta oil sands has resulted in the need for the reclamation of vast amounts of land. The low water holding capacity and nutrient retention of the available, coarse textured, reclamation soils make it challenging to re-create self-sustaining ecosystems. Furthermore, the reclamation of desired ecosites that occur in the Alberta oil sands can result in the need for specific soil conditions. There has been an extensive amount of research performed on the hydraulic properties of mineral soils as well as on how to utilize their physical properties to manipulate soil water and nutrients, aiding in the reclamation process. Many reclamation soils in the oil sands (such as LOS) however, are impregnated with PHC materials and there is limited scientific knowledge on how PHCs affect soil hydraulic properties. It is imperative that the effects of PHCs on the hydraulic properties of soils are well understood so that the use of these soils in reclamation can be optimized.

The overarching objective of this thesis research was to test the efficacy of LOS as the base soil layer in the reclamation of oil sands disturbed land. Two studies were designed to complete this objective. The first study tested the hydraulic properties of LOS with varying PHC concentrations and bulk densities. This study was intended, not only to provide insight on the effects that PHCs have on the hydraulic properties of LOS, but to also give an understanding of the physical mechanisms that control how the PHCs affect LOS hydraulic properties. The objective of the second study was to examine how heterogeneity of the PHC concentration and bulk density in the base LOS layer would affect the soil water storage and nutrient retention of the overlying reclamation profile.

The first study found that PHC concentration and bulk density both had an effect on the hydraulic properties of LOS. The water retention curves and the saturated hydraulic conductivity were measured. The increased compaction of the high bulk density LOS narrowed the porosity range and led to a significant reduction in mesopores and an increase in micropores. The low bulk density LOS had similar pore space in the mesopore size range as it did the micropore size range. An exception to this was seen when PHC concentration increased. Typically, organics would increase porosity in soil rather than decreasing it however, PHCs filled the pores of the soil and reduced the porosity. The PHC concentration mainly affected the microporosity of the LOS at higher concentrations (5.37% and 7.48%) due to the PHCs preferentially filling the micropores of the LOS. A downward trend in the mesoporosity was observed as PHC concentration increased, although the differences were not significant. Finally, the particle size analysis of the LOS showed that the 3.25% PHC concentration LOS had an appreciably higher amount of clay and silt, and less sand than the other samples. The elevated content of fine particles in the 3.25% LOS interrupted the downward trend of mesoporosity as PHC concentration increased, by significantly increasing the mesopore space of those samples. This effect was significant only in the mesoporosity of the high bulk density samples.

Since the increased bulk density reduced the porosity of LOS, the samples retained less water at saturation however, the high bulk density samples had higher AWHC. This results from the greater amount of pore space in the porosity ranges equivalent to field capacity and PWP in the high bulk density LOS than the low bulk density LOS. PHCs were found to fill the pores and further reduce the pore space available to water, so it is reasonable to conclude that increased PHC concentration led to the observed reduction in water retention of LOS. An exception to this trend was observed where an increase in saturated water content occurred when increasing from

0% PHC to 3.25% PHC, due to the increased clay content of the 3.25% LOS. Increased bulk density significantly reduced the $K_s$ of LOS, resulting from fewer large pores which conduct the water. The $K_s$ of LOS was also significantly reduced in the 3.25% PHC samples due to the elevated clay content. PHC concentration was also found to reduce the $K_s$ of LOS. This occurred at a lower PHC concentration in the high bulk density LOS because a larger proportion of smaller pores were filled by PHCs. Since macroporosity was unaffected by PHC concentration, the $K_s$ was likely reduced by the PHCs filling the connecting pores in the soil. The hydraulic properties of LOS with varying PHC concentration and bulk density were tested, however, how will they affect the hydraulic properties in the overlying reclamation profile, and what will this mean for reclamation success?

The second study in this thesis was designed to test how the soil water and nutrient dynamics would be affected by heterogeneity in the base LOS layer. It was demonstrated that the presence of a LOS layer increased the water storage and nutrient retention, and reduced the drainage of water out of the soil profile. Increasing bulk density of the LOS had the most significant effect on water and nutrient storage however, PHC concentration also affected the hydraulic properties in the overlying profile. Increased PHC concentration resulted in an increase in water storage under static (field capacity) and dynamic (replication of root water uptake below field capacity) conditions and slowed the drainage of water through the profile. In addition, an increase in PHC concentration in the low bulk density LOS resulted in an increase in nutrient retention and water storage under static and dynamic conditions in the overlying profile, similar to that of the column containing a LOS layer with a higher bulk density and clay concentration.

This research has led to a better understanding of how PHCs affect the hydraulic properties of soil. It has also shown that the use of LOS as a base layer will be beneficial for the reclamation of coarse textured soils with poor water and nutrient retention. The increased water and nutrient storage in the overlying profile may create more suitable soil conditions for the growth and establishment of vegetation. It may also be possible to use this new found knowledge to modify the soil layering prescriptions in a way that optimizes specific soil conditions, in order to achieve desired ecosites. Since the LOS was found to have higher AWHC as bulk density increased, LOS with higher bulk densities will not only retain more water in the overlying profile, but also retain more water within itself, for roots to access in drier conditions. Considering this, as well as previous work from Fleming (2012) who found little risk of contamination from the water leached out of similar hydrocarbon affected soils, the standards for placement depths of LOS in reclamation may be altered.

The research in this thesis also coincides with an on-going study which is looking at how the variability in tarballs within the reclamation soil matrix affects the performance of the reclamation soil cover. Together, these studies will result in a better understanding of how petroleum hydrocarbons in the base LOS layer as well as in the tarballs that lie within the reclamation cover material will affect the water dynamics in the reclamation profile. Future work should look at the variability of placement depth of LOS on the hydraulic properties of the overlying profile to determine if water and nutrient storage can be further optimized in this way. Future work will also look at using various parameters from this research, such as van Genuchten's (1980) $\alpha$ and $n$, to perform hydrologic modelling and provide predictions of soil hydraulic conditions under different layering scenarios. Long term monitoring and field testing at the ASCS will look at the hydraulic properties in the soil cover corresponding with different tree species. This will ultimately allow for the determination of potential ecosites that can be re-established in reclaiming the oil sand disturbed soils.

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# APPENDICES

# Appendix A

**Guide to determining soil moisture regime**

**Table A1** Guide to determining soil moisture regime. (CEMA, 2006)

| Moisture regime | Description | Idealized slope position[1] | Surface organic thickness (cm) | Water table depth (cm) | Primary water source | Common Texture[2] | Soil drainage class | Common ecosites[3] | Adjusted AWHC[4] (mm 100 cm) | SMR Index and Subclass |
|---|---|---|---|---|---|---|---|---|---|---|
| Very xeric (1) | Water removed extremely rapidly in relation to supply; soil is moist for a negligible time following precipitation. | 1 – 2 All | < 3 | >100 | Precipitation | Very coarse (gravel – S) Shallow soil | Very rapid | | <56[5] (40) | 10X |
| Xeric (2) | Water removed very rapidly in relation to supply; soil is moist for brief periods following precipitation. | 1 – 2 All | < 3 | >100 | Precipitation | Coarse (S) | Very rapid to rapid | a | 56 – 85 (70) | 24X |
| Subxeric (3) | Water remover rapidly in relation to supply; soil is moist for short periods following precipitation. | 2 – 3 Variable | < 3 | >100 | Precipitation | Coarse to moderately coarse (LS – SL) | Rapid | a, b | 86 – 115 (100) | 38X |
| Submesic (4) | Water removed readily in | 2 – 3 Variable | 3 – 5 | >100 | Precipitation | Moderately coarse | Rapid to well | b, c, d | 116 – 145 (130) | 52 |

| Moisture regime | Description | Idealized slope position[1] | Surface organic thickness (cm) | Water table depth (cm) | Primary water source | Common Texture[2] | Soil drainage class | Common ecosites[3] | Adjusted AWHC[4] (mm 100 cm) | SMR Index and Subclass |
|---|---|---|---|---|---|---|---|---|---|---|
| | relation to supply; water available for moderately short periods following precipitation. | | | | | (SL) | | | | |
| Mesic (5) | Water removed somewhat slowly in relation to supply; soil may remain moist for significant but sometimes short periods of the year; available soil water reflects climatic inputs. | 3 Variable | 6 – 9 | >100 | Precipitation in moderate to fine-textured soil and limited seepage in coarse-textured soils | Medium (SiL – L) to fine (SCL – C) Few coarse fragments | Well to moderately well | c, d | 146 – 175 (160) | 66 |
| Subhygric (6)[6] | Water removed slowly enough to keep the soil wet for a significant part of the growing season; some temporary seepage and | 4 Variable | 10 – 40 | May be < 100 | Precipitation and seepage | Variable depending on seepage | Imperfect | e, g | Equivalent to > 175 (190) | 80 |

| Moisture regime | Description | Idealized slope position[1] | Surface organic thickness (cm) | Water table depth (cm) | Primary water source | Common Texture[2] | Soil drainage class | Common ecosites[3] | Adjusted AWHC[4] (mm 100 cm) | SMR Index and Subclass |
|---|---|---|---|---|---|---|---|---|---|---|
| | possible mottling below 20 cm. | | | | | | | | | |
| Hygric (7a) [6] | Hygric aerated: Water removed slowly enough to keep the soil wet for most of the growing season; mottling present within 50 cm. | 5 – 7 | 16 – 40 | 30-100 | Permanent seepage; water table fluctuates often <100 cm | Variable depending on seepage | Poor | g, h, f | Wet | 66 |
| Hygric (7r) | Hygric reduced: Water removed slowly enough to keep the soil wet for most of the growing season; >50% gley within 50 cm. | 5 – 7 | 16 – 40 | 30-100 | Seepage; water table fluctuates often <100 cm | Variable depending on seepage | Poor | g, h, f | Wet | 24W |
| Subhydric (8) | Water removed slowly enough to keep the water table at or near surface for most of the | 5 – 7 | > 40 | 0-30 | Seepage or permanent water table <30 cm | Variable depending on seepage | Very poor | i, j, k | Wet | 0W |

| Moisture regime | Description | Idealized slope position[1] | Surface organic thickness (cm) | Water table depth (cm) | Primary water source | Common Texture[2] | Soil drainage class | Common ecosites[3] | Adjusted AWHC[4] (mm 100 cm) | SMR Index and Subclass |
|---|---|---|---|---|---|---|---|---|---|---|
| | year; organic and gleyed mineral soils; permanent seepage < 30 cm below soil surface. | | | | | | | | | |
| Hydric (9) | Water removed so slowly that the water table is at or above the soil surface all year; organic and gleyed mineral soils. | 5 – 7 | > 40 | 0 | Permanent surface water table | Variable depending on seepage | Very poor | l | Wet | 0W |

[1] See Figure 3 - Idealized slope positions do not take into account potentially significant scale effects; other indicators (such as common texture and vegetation) paramount.

[2] L = loam, S = sand, Si = silt, C = clay.

[6] Subhygric and hygric aerated moisture reqimes are to be applied only to natural soils.

[3] As defined by Beckingham and Archibald (1996).

[4] As determined from profile AWHC, layering modifiers and slope modifiers.

[5] Range (mode) (information from the Soil and Vegetation Plots)

# Appendix B

**Supporting Figures**

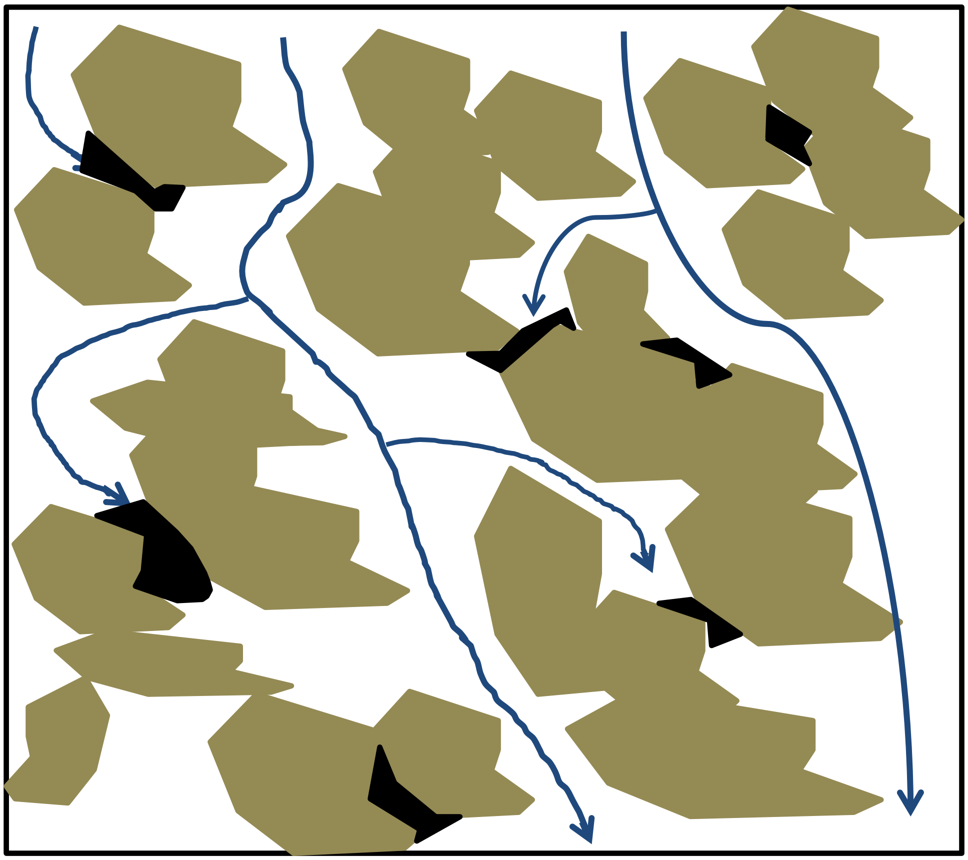

**Figure B1.** Representation of how PHCs fill the pores of LOS and block water flow, reducing the $K_s$ of the soil. The brown shapes represent soil particles, the black shapes represent PHCs in the pore space, and the blue lines represent the movement of water through the LOS.

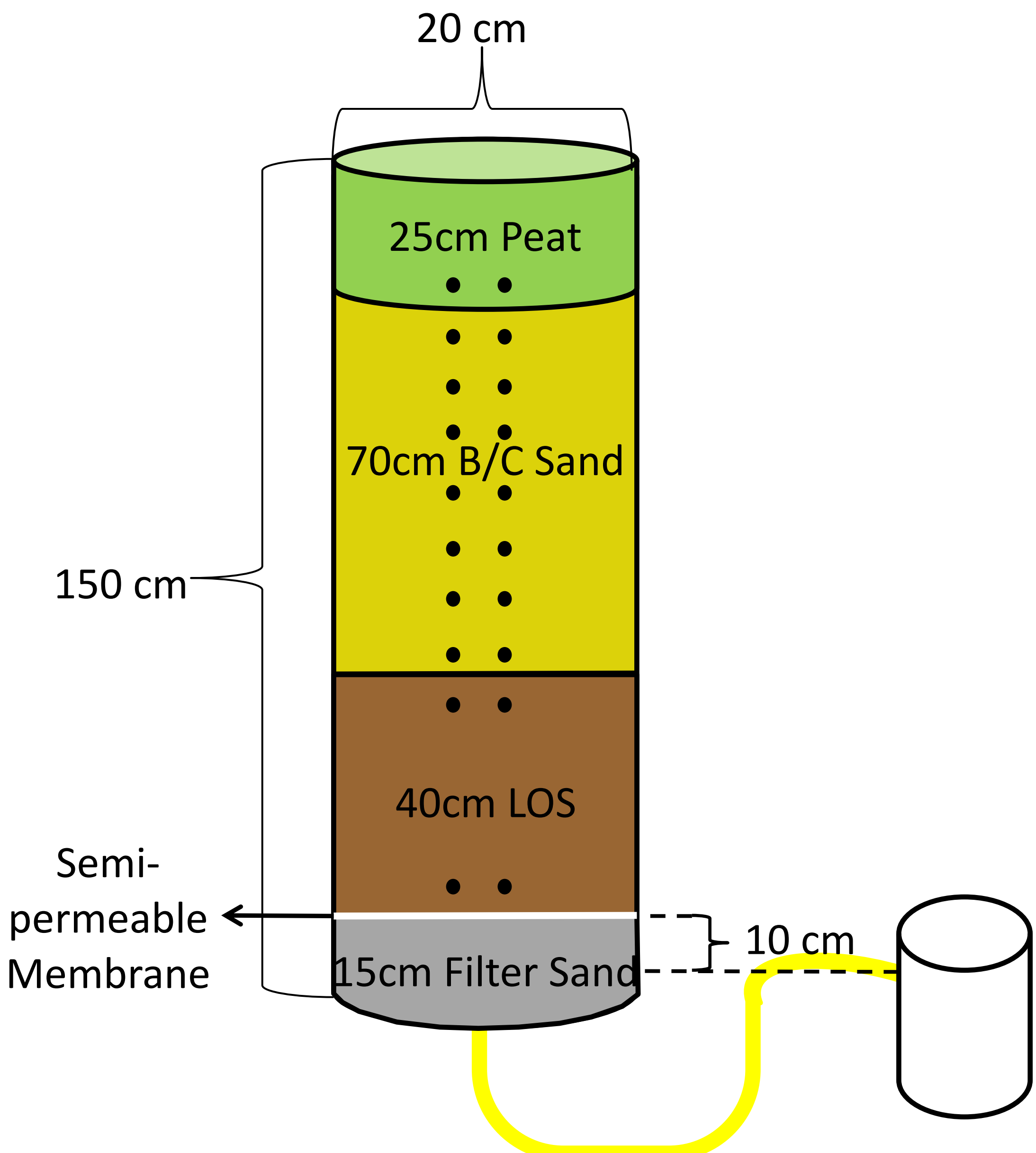


**Figure B2.** Setup for the column experiment. The black dots represent TDR ports and the yellow line at the bottom of the column represents the hose that is guiding the effluent to the collection pail.

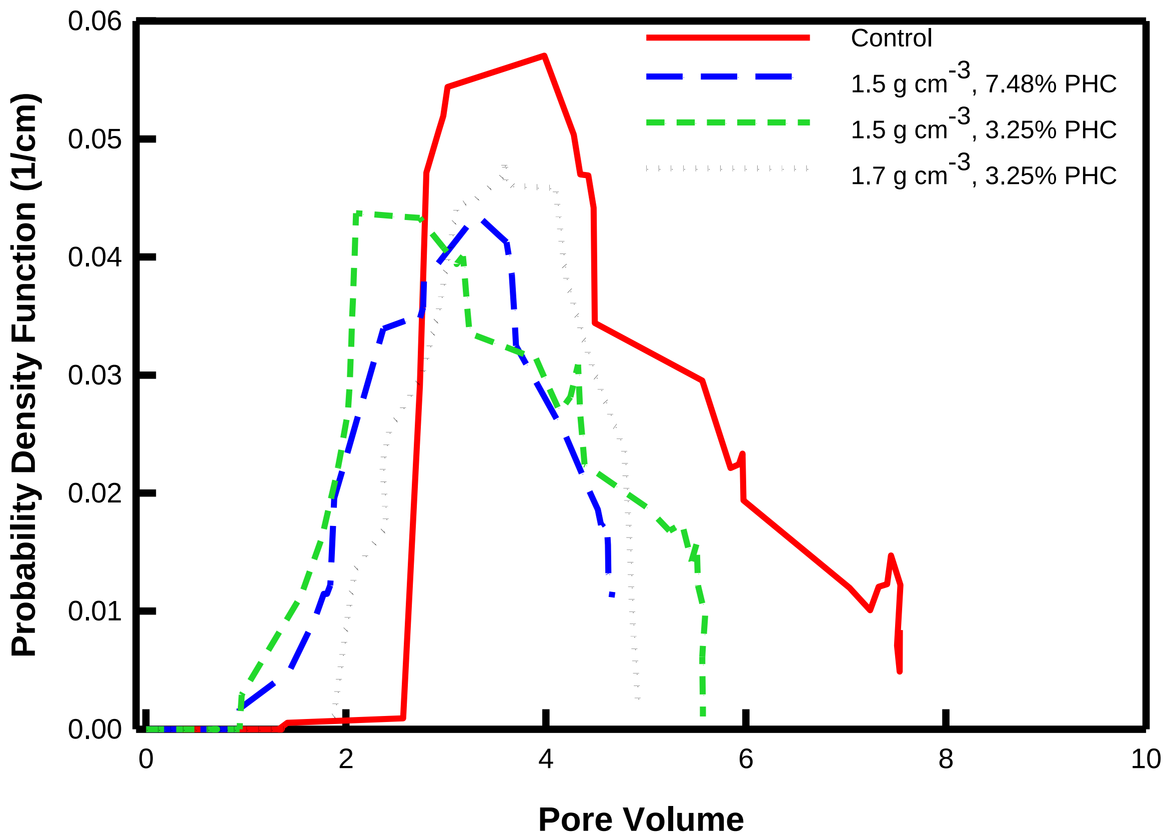


**Figure B3.** Nutrient breakthrough curves plotted as the probability density function over pore volume (1 pore volume = water storage at field capacity in each column).

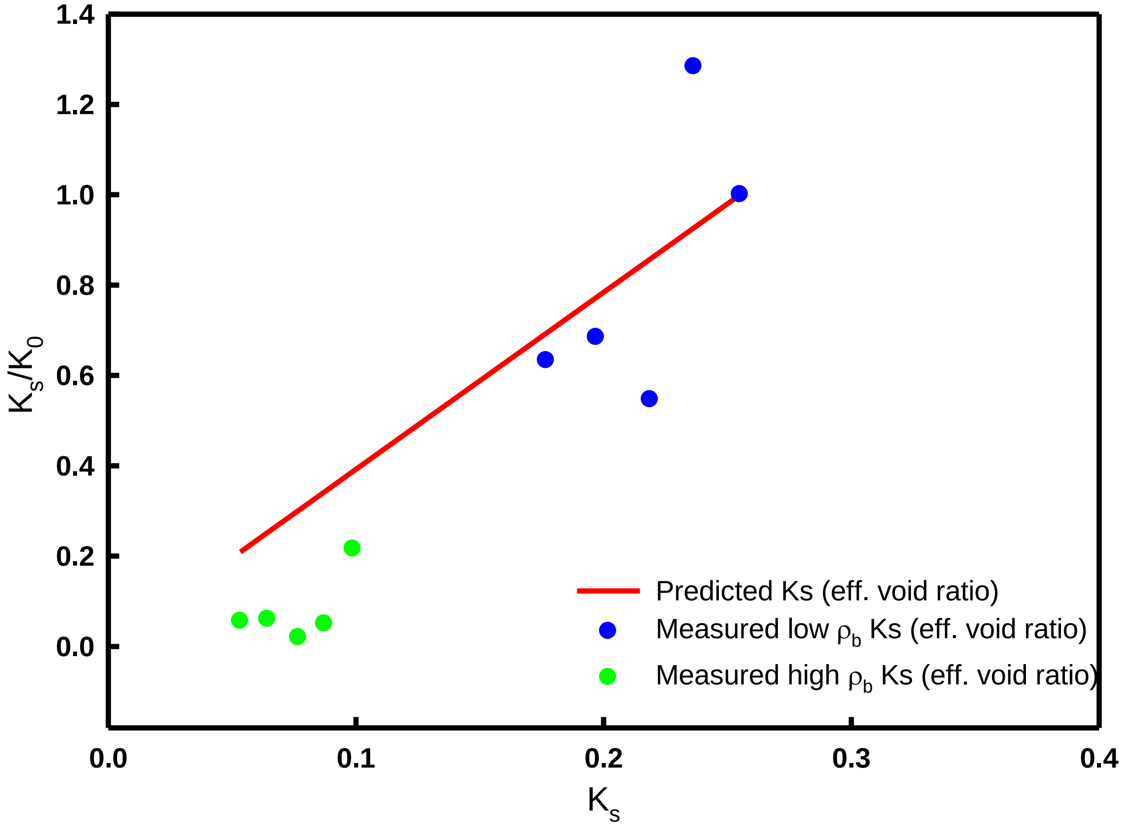


**Figure B4.** Normalized predicted Ks plotted over predicted Ks.

# Appendix C

## Data

**Table C1.** Raw and calculated saturated hydraulic conductivity data for the low bulk density LOS samples (1.5 g $cm^{-3}$).

| Core Height (cm) | Core Length (cm) | Core Diameter (cm) | | Sample Time (s) | 0.0% PHC Q ($cm^3$) | 0.0% PHC Ks (cm $h^{-1}$) | 1.63% PHC Q ($cm^3$) | 1.63% PHC Ks (cm $h^{-1}$) | 3.25% PHC Q ($cm^3$) | 3.25% PHC Ks (cm $h^{-1}$) | 5.37% PHC Q ($cm^3$) | 5.37% PHC Ks (cm $h^{-1}$) | 7.48% PHC Q ($cm^3$) | 7.48% PHC Ks (cm $h^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.54 | 5.08 | 5.08 | Rep 1 | 300 | 3.68 | 4.36 | 7.46 | 8.84 | 1.66 | 1.97 | 2.48 | 2.94 | 3.20 | 3.79 |
| | | | | 600 | 7.79 | 4.61 | 13.22 | 7.83 | 2.67 | 1.58 | 5.45 | 3.23 | 6.29 | 3.73 |
| | | | | 900 | 11.73 | 4.63 | 18.41 | 7.27 | 3.79 | 1.50 | 7.07 | 2.79 | 8.84 | 3.49 |
| | | | Rep 2 | 300 | 6.73 | 7.97 | 5.57 | 6.60 | 4.34 | 5.14 | 2.18 | 2.58 | 2.45 | 2.90 |
| | | | | 600 | 13.17 | 7.80 | 10.86 | 6.43 | 7.63 | 4.52 | 6.50 | 3.85 | 4.75 | 2.81 |
| | | | | 900 | 18.92 | 7.47 | 15.60 | 6.16 | 9.36 | 3.70 | 8.59 | 3.39 | 6.93 | 2.74 |
| | | | Rep 3 | 300 | 5.26 | 6.23 | 5.32 | 6.30 | 4.21 | 4.99 | 3.18 | 3.77 | 2.23 | 2.64 |
| | | | | 600 | 9.04 | 5.35 | 10.65 | 6.31 | 6.24 | 3.70 | 5.96 | 3.53 | 4.44 | 2.63 |
| | | | | 900 | 14.73 | 5.82 | 15.66 | 6.18 | 7.70 | 3.04 | 9.28 | 3.66 | 6.94 | 2.74 |
| | | | Rep 4 | 300 | 4.80 | 5.69 | 7.74 | 9.17 | 3.15 | 3.73 | 4.09 | 4.85 | 5.12 | 6.07 |
| | | | | 600 | 9.46 | 5.60 | 15.54 | 9.21 | 4.75 | 2.81 | 8.01 | 4.74 | 10.59 | 6.27 |
| | | | | 900 | 13.93 | 5.50 | 22.24 | 8.78 | 5.69 | 2.25 | 11.72 | 4.63 | 15.26 | 6.03 |
| | | | Rep 5 | 300 | 4.99 | 5.91 | 7.29 | 8.64 | 3.15 | 3.73 | 4.73 | 5.60 | 2.61 | 3.09 |
| | | | | 600 | 9.60 | 5.69 | 13.55 | 8.03 | 5.21 | 3.09 | 9.60 | 5.69 | 5.89 | 3.49 |
| | | | | 900 | 14.29 | 5.64 | 19.12 | 7.55 | 6.33 | 2.50 | 12.97 | 5.12 | 8.75 | 3.46 |

**Table C2.** Raw and calculated saturated hydraulic conductivity data for the high bulk density LOS samples (1.7 g $cm^{-3}$).

| | | | | Sample | 0.0% PHC | | 1.63% PHC | | 3.25% PHC | | 5.37% PHC | | 7.48% PHC | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Core Height (cm) | Core Length (cm) | Core Diameter (cm) | | Time (s) | Q ($cm^3$) | Ks (cm $h^{-1}$) | Q ($cm^3$) | Ks (cm $h^{-1}$) | Q ($cm^3$) | Ks (cm $h^{-1}$) | Q ($cm^3$) | Ks (cm $h^{-1}$) | Q ($cm^3$) | Ks (cm $h^{-1}$) |
| 2.54 | 5.08 | 5.08 | Rep 1 | 300 | 0.95 | 1.13 | 0.42 | 0.50 | 0.10 | 0.12 | 0.30 | 0.36 | 0.40 | 0.47 |
| | | | | 600 | 2.21 | 1.31 | 0.68 | 0.40 | 0.14 | 0.08 | 0.68 | 0.40 | 0.75 | 0.44 |
| | | | | 900 | 2.88 | 1.14 | 0.77 | 0.30 | 0.24 | 0.09 | 0.96 | 0.38 | 0.85 | 0.34 |
| | | | Rep 2 | 300 | 0.60 | 0.71 | 0.09 | 0.11 | 0.46 | 0.54 | 0.36 | 0.43 | 0.37 | 0.44 |
| | | | | 600 | 1.92 | 1.14 | 0.56 | 0.33 | 1.00 | 0.59 | 0.50 | 0.30 | 0.64 | 0.38 |
| | | | | 900 | 2.77 | 1.09 | 1.10 | 0.43 | 1.52 | 0.60 | 0.82 | 0.32 | 1.01 | 0.40 |
| | | | Rep 3 | 300 | 0.89 | 1.05 | 0.12 | 0.14 | 0.08 | 0.09 | 0.16 | 0.19 | 0.21 | 0.25 |
| | | | | 600 | 1.85 | 1.10 | 0.31 | 0.18 | 0.24 | 0.14 | 0.27 | 0.16 | 0.42 | 0.25 |
| | | | | 900 | 2.83 | 1.12 | 0.92 | 0.36 | 0.22 | 0.09 | 0.40 | 0.16 | 0.53 | 0.21 |
| | | | Rep 4 | 300 | 1.42 | 1.68 | 0.10 | 0.12 | 0.54 | 0.64 | 0.44 | 0.52 | 0.22 | 0.26 |
| | | | | 600 | 3.00 | 1.78 | 0.74 | 0.44 | 0.88 | 0.52 | 0.55 | 0.33 | 0.45 | 0.27 |
| | | | | 900 | 3.98 | 1.57 | 1.00 | 0.39 | 1.43 | 0.56 | 0.85 | 0.34 | 0.57 | 0.23 |
| | | | Rep 5 | 300 | 1.21 | 1.43 | 0.08 | 0.09 | 0.11 | 0.13 | 0.44 | 0.52 | 0.31 | 0.37 |
| | | | | 600 | 2.64 | 1.56 | 0.35 | 0.21 | 0.21 | 0.12 | 0.82 | 0.49 | 0.55 | 0.33 |
| | | | | 900 | 3.16 | 1.25 | 0.95 | 0.38 | 0.39 | 0.15 | 1.03 | 0.41 | 0.78 | 0.31 |

**Table C3.** Volumetric water content and curve fitting parameter data for the water retention curves of LOS.

| Treatment | | Volumetric Water Content ($cm^3\ cm^{-3}$) | | | | | | | | | Parameter | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pressure (cm) | | | | | | | | | | |
| $\rho_b$ (g $cm^{-3}$) | % PHC | 0 | 3 | 10 | 30 | 50 | 70 | 330 | 5000 | 15000 | $\alpha$ ($cm^{-1}$) | *n* |
| 1.5 | 0.00 | 0.436 | 0.424 | 0.423 | 0.355 | 0.321 | 0.301 | 0.206 | 0.099 | 0.090 | 0.052 | 1.464 |
| | 1.63 | 0.445 | 0.442 | 0.424 | 0.320 | 0.293 | 0.280 | 0.216 | 0.106 | 0.082 | 0.089 | 1.390 |
| | 3.25 | 0.471 | 0.471 | 0.468 | 0.346 | 0.312 | 0.297 | 0.232 | 0.103 | 0.072 | 0.072 | 1.402 |
| | 5.37 | 0.406 | 0.408 | 0.394 | 0.322 | 0.242 | 0.216 | 0.174 | 0.049 | 0.040 | 0.062 | 1.473 |
| | 7.48 | 0.339 | 0.338 | 0.333 | 0.252 | 0.226 | 0.210 | 0.139 | 0.043 | 0.026 | 0.066 | 1.430 |
| 1.7 | 0.00 | 0.377 | 0.373 | 0.374 | 0.363 | 0.344 | 0.321 | 0.240 | 0.103 | 0.093 | 0.021 | 1.495 |
| | 1.63 | 0.377 | 0.378 | 0.379 | 0.373 | 0.349 | 0.327 | 0.262 | 0.116 | 0.099 | 0.019 | 1.473 |
| | 3.25 | 0.402 | 0.396 | 0.391 | 0.354 | 0.324 | 0.309 | 0.244 | 0.087 | 0.077 | 0.036 | 1.424 |
| | 5.37 | 0.313 | 0.312 | 0.312 | 0.298 | 0.269 | 0.252 | 0.216 | 0.060 | 0.050 | 0.027 | 1.414 |
| | 7.48 | 0.261 | 0.262 | 0.264 | 0.262 | 0.236 | 0.218 | 0.167 | 0.026 | 0.020 | 0.019 | 1.481 |

**Table C4.1.** Volumetric water content and total water storage (from above LOS layer) measured from TDR rods in Column 1 (control) at different depths and times during the experiment.

| | Volumetric Water Content ($cm^3\ cm^{-3}$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TDR Depth (cm) | | | | | | | | | | | |
| Elapsed Time (hrs) | 20 (Peat) | 30 (B/C) | 40 (B/C) | 50 (B/C) | 60 (B/C) | 70 (B/C) | 80 (B/C) | 90 (B/C) | 100 (LOS) | 130 (LOS) | Water Storage (cm) | Column Conditon |
| 0.37 | 0.626 | 0.406 | 0.383 | 0.371 | 0.37 | 0.415 | 0.42 | 0.437 | 0.39 | 0.357 | 43.67 | Saturation 1 |
| 72.70 | 0.12 | 0.038 | 0.037 | 0.036 | 0.038 | 0.054 | 0.059 | 0.065 | 0.062 | 0.336 | 6.27 | Field Capacity 1 |
| 312.93 | 0.122 | 0.034 | 0.024 | 0.023 | 0.025 | 0.038 | 0.046 | 0.056 | 0.053 | 0.268 | 5.51 | Pressure 1 |
| 431.73 | 0.118 | 0.025 | 0.021 | 0.021 | 0.025 | 0.047 | 0.055 | 0.062 | 0.054 | 0.189 | 5.51 | After Pressure 1 |
| 433.53 | 0.165 | 0.091 | 0.094 | 0.101 | 0.096 | 0.129 | 0.127 | 0.123 | 0.058 | 0.188 | 11.74 | Pressure 2 |
| 578.93 | 0.087 | 0.03 | 0.025 | 0.023 | 0.031 | 0.049 | 0.053 | 0.061 | 0.057 | 0.219 | 4.90 | After Pressure 2 |
| 793.83 | 0.602 | 0.385 | 0.332 | 0.288 | 0.295 | 0.306 | 0.332 | 0.3 | 0.317 | 0.27 | 37.43 | Saturation 2 |
| 865.60 | 0.132 | 0.053 | 0.036 | 0.031 | 0.041 | 0.073 | 0.074 | 0.088 | 0.072 | 0.271 | 7.26 | Field Capacity 2 |
| 887.60 | 0.133 | 0.048 | 0.037 | 0.188 | 0.04 | 0.07 | 0.069 | 0.084 | 0.073 | 0.271 | 8.69 | Tracer and Rain |
| 1248.27 | 0.134 | 0.042 | 0.028 | 0.03 | 0.032 | 0.057 | 0.058 | 0.075 | 0.08 | 0.08 | 6.57 | Long drainage |

**Table C4.2.** Volumetric water content and total water storage (from above LOS layer) measured from TDR rods in Column 2 at different depths and times during the experiment.

| | Volumetric Water Content (cm$^3$ cm$^{-3}$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TDR Depth (cm) | | | | | | | | | | | |
| Elapsed Time (hrs) | 20 (Peat) | 30 (B/C) | 40 (B/C) | 50 (B/C) | 60 (B/C) | 70 (B/C) | 80 (B/C) | 90 (B/C) | 100 (LOS) | 130 (LOS) | Water Storage (cm) | Column Condtion |
| 1.03 | 0.413 | 0.55 | 0.343 | 0.382 | 0.39 | 0.38 | 0.363 | 0.357 | 0.257 | 0.067 | 37.98 | Saturation 1 |
| 311.67 | 0.276 | 0.068 | 0.07 | 0.079 | 0.111 | 0.184 | 0.258 | 0.338 | 0.254 | 0.284 | 17.98 | Field Capacity 1 |
| 312.00 | 0.275 | 0.069 | 0.072 | 0.078 | 0.11 | 0.18 | 0.259 | 0.334 | 0.253 | 0.284 | 17.90 | Pressure 1 |
| 430.83 | 0.212 | 0.054 | 0.059 | 0.065 | 0.08 | 0.069 | 0.069 | 0.074 | 0.246 | 0.285 | 10.00 | After Pressure 1 |
| 432.33 | 0.301 | 0.118 | 0.13 | 0.136 | 0.158 | 0.152 | 0.161 | 0.162 | 0.247 | 0.287 | 17.70 | Pressure 2 |
| 578.00 | 0.198 | 0.053 | 0.061 | 0.064 | 0.08 | 0.069 | 0.071 | 0.076 | 0.245 | 0.284 | 9.69 | After Pressure 2 |
| 813.67 | 0.679 | 0.389 | 0.359 | 0.282 | 0.302 | 0.277 | 0.269 | 0.265 | 0.252 | 0.291 | 38.41 | Saturation 2 |
| 886.67 | 0.252 | 0.139 | 0.153 | 0.278 | 0.293 | 0.266 | 0.257 | 0.259 | 0.252 | 0.287 | 22.75 | Field Capacity 2* |
| 911.00 | 0.283 | 0.193 | 0.28 | 0.287 | 0.298 | 0.269 | 0.259 | 0.261 | 0.254 | 0.285 | 25.55 | Tracer and Rain |
| 1247.00 | 0.08 | 0.08 | 0.078 | 0.079 | 0.08 | 0.08 | 0.119 | 0.259 | 0.25 | 0.285 | 9.75 | Long drainage |

***** Field capacity 2 was measured after only 46 hours in this column because it took longer for the hydraulic head to drop to the level of the soil in the column for drainage time to begin.

**Table C4.3.** Volumetric water content and total water storage (from above LOS layer) measured from TDR rods in Column 3 at different depths and times during the experiment.

| | Volumetric Water Content ($cm^3\ cm^{-3}$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TDR Depth (cm) | | | | | | | | | | | |
| Elapsed Time (hrs) | 20 (Peat) | 30 (B/C) | 40 (B/C) | 50 (B/C) | 60 (B/C) | 70 (B/C) | 80 (B/C) | 90 (B/C) | 100 (LOS) | 130 (LOS) | Water Storage (cm) | Column Condition |
| 1.03 | 0.636 | 0.325 | 0.368 | 0.371 | 0.367 | 0.372 | 0.368 | 0.357 | 0.314 | 0.304 | 37.98 | Saturation 1 |
| 311.67 | 0.221 | 0.057 | 0.066 | 0.074 | 0.068 | 0.071 | 0.058 | 0.073 | 0.202 | 0.312 | 17.98 | Field Capacity 1 |
| 312.00 | 0.211 | 0.047 | 0.059 | 0.064 | 0.059 | 0.061 | 0.054 | 0.063 | 0.198 | 0.316 | 17.90 | Pressure 1 |
| 430.83 | 0.175 | 0.034 | 0.053 | 0.060 | 0.057 | 0.059 | 0.050 | 0.061 | 0.182 | 0.316 | 10.00 | After Pressure 1 |
| 432.33 | 0.258 | 0.088 | 0.104 | 0.121 | 0.115 | 0.130 | 0.126 | 0.166 | 0.222 | 0.317 | 17.70 | Pressure 2 |
| 578.00 | 0.176 | 0.034 | 0.056 | 0.064 | 0.061 | 0.061 | 0.053 | 0.070 | 0.208 | 0.331 | 9.69 | After Pressure 2 |
| 813.67 | 0.602 | 0.358 | 0.372 | 0.331 | 0.308 | 0.322 | 0.284 | 0.311 | 0.295 | 0.336 | 38.41 | Saturation 2 |
| 886.67 | 0.219 | 0.049 | 0.062 | 0.067 | 0.066 | 0.072 | 0.055 | 0.082 | 0.264 | 0.338 | 22.75 | Field Capacity 2* |
| 911.00 | 0.220 | 0.049 | 0.059 | 0.068 | 0.062 | 0.070 | 0.052 | 0.086 | 0.260 | 0.336 | 25.55 | Tracer and Rain |
| 1247.00 | 0.214 | 0.035 | 0.054 | 0.060 | 0.061 | 0.065 | 0.049 | 0.063 | 0.206 | 0.331 | 9.75 | Long drainage |

**Table C4.4.** Volumetric water content and total water storage (from above LOS layer) measured from TDR rods in Column 4 at different depths and times during the experiment.

| | Volumetric Water Content ($cm^3$ $cm^{-3}$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TDR Depth (cm) | | | | | | | | | | | |
| Elapsed Time (hrs) | 20 (Peat) | 30 (B/C) | 40 (B/C) | 50 (B/C) | 60 (B/C) | 70 (B/C)* | 80 (B/C) | 90 (B/C) | 100 (LOS) | 130 (LOS) | Water Storage (cm) | Column Condition |
| 49.33 | 0.634 | 0.387 | 0.369 | 0.376 | 0.369 | 0.355 | 0.382 | 0.337 | 0.52 | 0.349 | 41.81 | Saturation 1 |
| 122.17 | 0.21 | 0.072 | 0.056 | 0.054 | 0.05 | -0.653 | 0.093 | 0.087 | -0.44 | 0.343 | 10.09 | Field Capacity 1 |
| 238.17 | 0.198 | 0.065 | 0.048 | 0.045 | 0.041 | -0.533 | 0.08 | 0.076 | -0.54 | 0.347 | 9.11 | Pressure 1 |
| 357.00 | 0.163 | 0.055 | 0.04 | 0.037 | 0.038 | -0.564 | 0.072 | 0.069 | 0.509 | 0.371 | 7.74 | After Pressure 1 |
| 358.60 | 0.235 | 0.129 | 0.113 | 0.108 | 0.107 | -0.684 | 0.165 | 0.161 | 0.502 | -0.448 | 15.07 | Pressure 2 |
| 504.17 | 0.157 | 0.053 | 0.043 | 0.042 | 0.039 | -0.583 | 0.076 | 0.076 | -0.494 | 0.353 | 7.79 | After Pressure 2 |
| 757.83 | 0.445 | 0.244 | 0.348 | 0.311 | 0.238 | -0.603 | 0.306 | 0.273 | 0.457 | -0.527 | 31.05 | Saturation 2 |
| 802.83 | 0.209 | 0.066 | 0.059 | 0.056 | 0.073 | -0.804 | 0.293 | 0.26 | 0.455 | 0.361 | 15.13 | Field Capacity 2** |
| 812.83 | 0.205 | 0.064 | 0.057 | 0.055 | 0.053 | -0.697 | 0.289 | 0.261 | -0.512 | 0.359 | 14.63 | Tracer and Rain |
| 1173.17 | 0.195 | 0.053 | 0.046 | 0.045 | 0.042 | -0.581 | 0.081 | 0.084 | 0.339 | 0.347 | 9.00 | Long drainage |

*The water contents at 70 cm of depth were not used for the water storage measurement as the data was no good for that TDR.
** Field capacity 2 was measured after only 46 hours in this column because it took longer for the hydraulic head to drop to the level of the soil in the column for drainage time to begin.

**Table C4.5.** Volumetric water content and total water storage (from above LOS layer) measured from TDR rods in Column 5 at different depths and times during the experiment.

| | Volumetric Water Content ($cm^3$ $cm^{-3}$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TDR Depth (cm) | | | | | | | | | | | |
| Elapsed Time (hrs) | 20 (Peat) | 30 (B/C) | 40 (B/C) | 50 (B/C) | 60 (B/C) | 70 (B/C) | 80 (B/C) | 90 (B/C) | 100 (LOS) | 130 (LOS) | Water Storage (cm) | Column Condition |
| 1.60 | 0.593 | 0.364 | 0.349 | 0.357 | 0.352 | 0.366 | 0.364 | 0.327 | 0.369 | 0.365 | 39.62 | Saturation 1 |
| 73.77 | 0.199 | 0.06 | 0.033 | 0.031 | 0.033 | 0.043 | 0.061 | 0.064 | 0.297 | 0.395 | 8.23 | Field Capacity 1 |
| 237.10 | 0.308 | 0.052 | 0.025 | 0.024 | 0.022 | 0.026 | 0.041 | 0.047 | 0.289 | 0.414 | 10.07 | Pressure 1 |
| 355.93 | 0.501 | 0.043 | 0.019 | 0.02 | 0.017 | 0.027 | 0.04 | 0.046 | 0.268 | 0.41 | 14.65 | After Pressure 1 |
| 357.57 | 0.206 | 0.105 | 0.079 | 0.086 | 0.084 | 0.1 | 0.124 | 0.136 | 0.276 | 0.407 | 12.29 | Pressure 2 |
| 503.17 | 0.117 | 0.039 | 0.024 | 0.022 | 0.021 | 0.031 | 0.045 | 0.049 | 0.278 | 0.404 | 5.24 | After Pressure 2 |
| 726.93 | 0.694 | 0.389 | 0.31 | 0.271 | 0.242 | 0.248 | 0.288 | 0.259 | 0.365 | 0.375 | 37.42 | Saturation 2 |
| 799.77 | 0.142 | 0.051 | 0.03 | 0.032 | 0.031 | 0.037 | 0.052 | 0.071 | 0.305 | 0.38 | 6.59 | Field Capacity 2 |
| 811.73 | 0.151 | 0.049 | 0.028 | 0.033 | 0.032 | 0.037 | 0.049 | 0.067 | 0.306 | 0.38 | 6.73 | Tracer and Rain |
| 1172.10 | 0.133 | 0.044 | 0.023 | 0.027 | 0.026 | 0.034 | 0.045 | 0.053 | 0.307 | 0.381 | 5.85 | Long drainage |